

**CHARACTERIZATION, MAPPING, AND EVALUATION OF
RECLAMATION RESOURCES FOR SOILS AROUND ABAYA
AND CHAMO LAKES, SOUTHERN ETHIOPIAN RIFT VALLEY**



PhD DISSERTATION

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HAWASSA UNIVERSITY

COLLEGE OF AGRICULTURE

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**CHARACTERIZATION, MAPPING, AND EVALUATION OF
RECLAMATION RESOURCES FOR SOILS AROUND ABAYA
AND CHAMO LAKES, SOUTHERN ETHIOPIAN RIFT VALLEY**

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DEDICATION

This doctoral dissertation honors in loving memory of my father, Walche Mengesha, who passed away. He dreamed of me reaching this stage as his son, and if he had not laid the foundation and encouraged me, I would not have been at this stage. My dedication also goes to the civilians of Ethiopia who died in the civil war in Northern Ethiopia, the civilians who died here and there in the country due to conflicts, and the civilians who died throughout the world because of COVID-19 during the journey of my PhD study period.

DECLARATION

I declare that this PhD dissertation is my original work and that all sources of materials used in this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for the Doctor of Philosophy (PhD) degree in Soil Science at Hawassa University. This document is placed at the Hawassa University library to be made available for users under the rules and regulations of the University. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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BIOGRAPHICAL SKETCH

The author, Azmera Walche Mengesha, was born on 09 January 1986 in Arba Minch Zuria District, Chano Mile Kebele, South Ethiopia. He attended primary school at Chano Dorga kebele from 1995 to 2001. In junior and secondary education, he attended Abaya Junior School and Arba Minch Secondary and Preparatory School from 2002 to 2004, respectively. He joined the Ministry of Agriculture and Rural Development Alage Agricultural Technical Vocational Education and Training College in 2005 and graduated with a Diploma in Plant Science in 2007. He was then recruited and began his professional career in the Department of Horticulture in the College of Agricultural Science at Arba Minch University (AMU). He served as a technical assistant in different ranks at AMU from 2007 to 2013. He started the Bachelor of Science in Horticulture program in 2009 and graduated with a BSc Degree in Horticulture in 2013 from AMU. Then, the author was recruited and promoted the same year to a Graduate Assistant rank and served one year in the Department of Horticulture in the College of Agricultural Sciences, AMU.

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Then, he joined the PhD program at Hawassa University, College of Agriculture, the School of Plant and Horticultural Sciences in 2017/2018 with the sponsorship of the MoE and AMU-IUC Project 4 of Ethiopia to pursue his PhD studies in Soil Science.

LIST OF ABBREVIATIONS AND ACRONYMS

AMU	Arba Minch University
ANOVA	Analysis of Variance
AWC	Available Water Content
AWHC	Available Water Holding Capacity
CASCAPE	Capacity building for Scaling up of evidence-based best practices in Agricultural Production in Ethiopia
CV	Coefficient of Variation
DEM	Digital Elevation Model
DTPA	Di-Ethylene Tri-Amine Penta-Acetic acid
ESP	Exchangeable Sodium Percentage
EthioSIS	Ethiopia Soil Information System
FYM	Farm Yard Manure
FAO	Food and Agriculture Organization of United Nations
GIS	Geographic Information System
GPS	Geographic Positioning System
GR	Gypsum Requirement
ITCZ	Inter-Tropical Convergence Zone
IUC	Institutional University Cooperation
LSD	Least Significant Difference
PCA	Principal Component Analysis
SAR	Sodium Adsorption Ratio
SAS	Statistical Analysis System
USSLS	United States of Soil Laboratory Staff
UTM	Universal Transverse Mercator
VLIR-IUC	Vlaamse Inter-Universitaire Raad-Institutional University Cooperation
WoSIS	World Soil Information System

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LIST OF ARTICLES AND MANUSCRIPTS

This dissertation comprises the following manuscripts in chapters: Four articles have already been published in a reputable journal (listed in section 7 appendices), and a fifth manuscript has been submitted for publication and is under review.

Azmera Walche, Wassie Haile, Alemayehu Kiflu, and Dereje Tsegaye. Assessment and Characterization of Agricultural Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley. *Applied and Environmental Soil Science Journal, Hindawi*, <https://doi.org/10.1155/2023/3946508>.

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Characterization, Mapping, and Evaluation of Reclamation Resources for Soils around Abaya and Chamo Lakes, Southern Ethiopian Rift Valley

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ABSTRACT

Characterizing and understanding the nature of the soil and its management are crucial for successful crop production. With this in mind, experiments were conducted to (1) characterize of soils surrounding Lakes Abaya and Chamo, (2) analyze nutrient contents and map the fertility status of agricultural soils, (3) determine the intensity and types of soils and map their spatial distribution patterns, and (4) investigate the efficacy of gypsum and farmyard manure and their combined application in reclaiming sodic soil's chemical and physical properties. The first study revealed that the soil properties in the study site were highly heterogeneous in terms of morphological, physical, and chemical characteristics. Most of the studied soils were highly alkaline (>8.5), had very high sodium content ($>20 \text{ cmolc kg}^{-1}$), very high CEC value ($> 40 \text{ cmolc kg}^{-1}$), very low TN ($<0.1\%$), and low levels of organic carbon (0.5-1.5%) and exchangeable calcium ($2-5 \text{ cmolc kg}^{-1}$). The study recommended removing sodium and salts from the soil depth to improve the productivity of agricultural soils in the area. Applying organic amendments such as manures and crop residues was also suggested to increase fertility and organic matter content. The second study showed the soil texture in the area was mainly clay, heavy clay (Ganta Kanchama site), and sandy clay loam. The surface soil had a higher available water holding capacity than the subsurface depth, indicating more plant water storing space. The soils in the studied area had an alkaline pH, moderately ($2-4 \text{ dSm}^{-1}$) to highly saline ($4-8 \text{ dSm}^{-1}$) EC values, high exchangeable sodium percentage (50-70%), high soil CEC, low OC, very low total nitrogen content, high potassium availability ($>300 \text{ mg kg}^{-1}$), and

lower calcium carbonate content. The study showed the soils of the area were fertile, however, incorporating organic matter into the soil enhances its structure, water retention, and nutrient availability, reducing salinity and sodicity. The results of the third experiment revealed that the study area has moderately (7.9-8.4) to strongly alkaline soil pH (8.5-9.0), slightly (0.75-2 dS m⁻¹) to moderately saline (2-4 dS m⁻¹) EC values, and a high variability in soil ESP values, indicating a strong variability in soil sodicity across different parts of the study area. Out of 2274.65 ha of the studied area, 62.28%, 26.09%, 10.99%, and 0.63% were categorized as non-saline non-sodic, saline-sodic, sodic, and saline, respectively. The results showed that almost all salt-affected sites were situated in relatively low-lying slope (0-2 %) areas, flat to almost flat slopes. The findings suggest that the place needs specific soil management strategies to address the salinity and sodicity problems. The last study investigated the impact of amendment resources on sodic soils. A pot experiment consisting of a factorial combination of four levels of GYP (0, 50, 100, and 150%) and four levels of FYM (0, 10, 20, and 30 tons ha⁻¹), with Complete Randomized Design (CRD and three replications was used. The results showed that applying gypsum (GYP) and farmyard manure (FYM) reduced exchangeable sodium percentage (ESP) in sodic soils. Specifically, using 10 ton FYM ha⁻¹ and GYP at 100% GYP required (GR) rate resulted in a 99.8% decrease in ESP compared to untreated composite sodic soil. The study also indicated optimal amendment levels (combined application of 100% GYP and 10 ton FYM ha⁻¹) for displacing exchangeable sodium from the exchange site using prediction models. Agglomerative hierarchical and K-means cluster analysis suggest that treatment levels and reclaimed soils with similar properties require application of comparable treatment levels and similar management. The study found that combined applications of GYP (at 100% gypsum requirement rate) and FYM (10 ton FYM ha⁻¹) reduced ESP to less than 10% in agricultural soil. However, further research is needed to determine their effectiveness at the field level.

Keywords: Semi-arid region, incubation, salt intensity and types, reclamation, soil fertility status, soil properties

1. GENERAL INTRODUCTION AND DESCRIPTION OF THE STUDY AREA

1.1 Background of the Study

The main biophysical prerequisite for increasing food production in Sub-Saharan African nations is to restore soil fertility (Bekunda et al., 2010; Stewart et al., 2020). For centuries, agricultural production in Ethiopia, where it is the backbone of the national economy, has been heavily reliant on natural resources (Neglo et al., 2021; Yigezu Wendimu, 2021). The ultimate sustainability of every agricultural system is determined by the soil, a dynamic and slowly replenishable natural resource (Barati et al., 2019; Doran et al., 2018). Soil is related to vegetation productivity, land use, water movement, and water quality. In order to support the requirements of humans and animals, soils produce food, fodder, and fuel (Brevik et al., 2020; Liu et al., 2021). However, as a result of changes in soil properties brought about by the increasing population's need for food, nutrients have been depleted and soil productivity has decreased (Alemineu and Alemayehu, 2020). This necessitates a methodical assessment of soil resources in terms of their extent, distribution, characteristics, and potential for use. This is crucial for creating a land use system that will effectively increase agricultural output while maintaining sustainability (Fekadu et al., 2018; Ronchi et al., 2019; Sahu et al., 2015). For sustainable agricultural production, it is important to address the mismatch between fertilizer types and crop nutrient demand; it is imperative to understand the site-specific variability in nutrient supply before applying nutrients (Malhi et al., 2022; Sarkar et al., 2017). Especially in the arid and semi-arid regions, the areas that are affected by salt, it is essential to assess and understand the nature of soil regarding nutrient application and other management strategies (El Sabagh et al., 2020).

Soils affected by salt are found across the world, and no continent is exempted from this problem (Basak et al., 2022; Chhabra and Chhabra, 2021b). Salinity and sodicity are rendering a significant amount of land unproductive each year. One billion hectares of land worldwide are affected by salt. Salt affects African nations to varying degrees, including Kenya (8.2 Mha), Nigeria (5.6 Mha), Sudan (4.8 Mha), Tunisia (1.8 Mha), Tanzania (1.7 Mha), and Ghana (0.79 Mha) (Alemayehu et al., 2016; Alemayehu, 2018; FAO, 2020). According to reports, salt affects almost 11 million hectares of Ethiopian soil (Daba and Qureshi, 2021; Qureshi et al., 2019). The arid and semi-arid lowlands as well as the Rift Valley regions, which are distinguished by a higher rate of evapotranspiration in relation to precipitation, are usually host to Ethiopia's naturally salt-affected areas.

An increasing problem is soil salinization, particularly in arid and semi-arid areas where irrigation is practiced. An alarming rise in salinity and sodicity-related degradation of soil is threatening the environment, agricultural ecosystems, and human life (Ayub et al., 2020; Bortolini et al., 2018; Salcedo et al., 2022; Yin et al., 2022). This problem deleteriously impacts soil fertility, reducing soil productivity (Daba and Qureshi, 2021; Habtamu and Wassie, 2022; Hailu and Mehari, 2021; Walche et al., 2023). Aside from this, problems with water infiltration, air movement, root penetration, and seedling emergence are ultimately brought on by the change in soil physical characteristics led on by the expansion and dispersion of soil colloidal particles caused on by additional exchangeable Na (Choudhary and Kharche, 2018; Daba and Qureshi, 2021; Worku and Bedadi, 2016).

The existing geo-referenced soil fertility status (Worku et al., 2015), irrigation methods for water management (Tessema et al., 2023), and the chemical and physical characteristics of the soil that cause the problem of soils must all be identified in order to find solutions to these problems. Because of the hot and dry weather, farmers are forced to use poor quality irrigation water that contains soluble salts in proportions that would damage susceptible plants and/or adversely affect the properties of the soil (Hailu and Mehari, 2021; Zaman et al., 2018). All crops cultivated in these arid and semi-arid environments lack access to enough water in sufficient amounts to meet their requirements for water. Farmers feel obliged to use all available irrigation water sources in this scenario (Golla, 2021; Hussain et al., 2019). Soils affected by salt were frequently developed gradually due to this practice. Therefore, understanding the types and characteristics of soils and the quality of irrigation water is essential for making decisions about crop productivity and soil management (Mandal et al., 2018; Singh, 2021).

Given this, soil assessment and characterization have been conducted across different parts of Ethiopia to determine the kinds and properties of soils suitable for soil management practice (Dinssa and Elias, 2021; Negasa et al., 2017). Characterizing the soil facilitates information sharing and technology transfer between soil scientists, planners, researchers, decision-makers, and advisers on agricultural extension (Eichler Inwood and Dale, 2019; Lobry de Bruyn et al., 2017). In order to give baseline data on the physical, chemical, and mineralogical properties of the soil for precision agriculture, land use planning and management, a thorough examination of the evaluation and characterization of the soil is necessary (Fekadu et al., 2018; Malone et al., 2022; Seifu et al., 2022). Understanding the basics of soils, their formation, distribution

around the world, and potential responses to management and use are all necessary for developing a soil map (Brevik et al., 2016). Applying suitable agricultural technologies and designing practical soil fertility management strategies can be aided by soil fertility analysis, which looks at the physical, chemical, and biological characteristics of the soil and maps them (Malla et al., 2020; Metwally et al., 2019).

Another goal of soil mapping is to fill in knowledge gaps about the characteristics and processes of soil in both space and time (Baveye et al., 2018; Camps-Valls et al., 2016). Improving and maintaining soil fertility and productivity requires ongoing monitoring of essential soil parameters and how they respond to changes in land use (Masto et al., 2008; Mayel et al., 2021). To obtain information for current and future purposes, it is also necessary to map the spatial variability of soil fertility regarding salt-affected soil using a geographic information system (GIS). Determining the soil nutrients and fertilizer requirements for areas with low soil fertility, tracking changes in soil fertility due to soil dynamics altered by salt, and drawing boundaries around soil fertility are all possible with soil fertility mapping (Rahul et al., 2019; Ray et al., 2015; Worku et al., 2015).

Recently, a soil fertility map has been developed by the Ethiopian Soil Information System (Ethio SIS) to provide fertilizer recommendations across the country's diverse areas (Hordofa, 2020), and the country's thirty districts have picked soil maps from the capacity-building for scaling up of evidence-based best practices in agricultural production in Ethiopia (CASCAPE) project (Ali et al., 2020; Leenaars et al., 2016). These necessitate the analysis and mapping of soil fertility to monitor changes and reveal soil fertility status under different soils and soil types (Barman et al., 2021). The majority of the country's limited soil maps are smaller-scale representations of scattered areas with insufficient analytical data, which makes them of limited information for essential interpretations and site-specific land use decision-making (Fekadu et al., 2018a; Hengl and MacMillan, 2018). Therefore, in order to accurately predict and map soil patterns and distribution, it is essential to do thorough salt-affected soil analysis and mapping. This will help better understand soil resources (Nabiollahi et al., 2021). Consequently, a great deal of research has been done on the characteristics of sodic and saline soils and how to improve them, especially in terms of soil physical properties (Leogrande and Vitti, 2019; Miranda et al., 2018). In saline soils, leaching has been found to be the most efficient technique for removing soluble salts from the rhizosphere (Srivastava et al., 2019) while to reclaim sodic soils, chemical amendments have to be applied in order to remove sodium from the soil's cation

exchange sites (Noori et al., 2021). It is possible to improve saline-sodic soils and produce a high-quality crop by using appropriate management techniques.

To improve farm management and crop production in saline-sodic soil, it is crucial to create the most appropriate reclamation technique or a combination of technologies. Gypsum (GYP) is the most widely utilized beneficial amendment because it is inexpensive (Gangwar et al., 2020; Mohammad et al., 2018; Shahid et al., 2018). The combined use of farm yard manure (FYM) and GYP has a beneficial effect on the reclamation of sodic soils. Reclamation of sodic soils usually succeeds by reducing the amount of Na^+ ions and raising Ca^{2+} on the exchange sites. By leaching water, the replaced Na^+ is removed either below the root zone or outside of the profile (Hailu and Mehari, 2020; Osman and Osman, 2018; Prapagar et al., 2012). Increased soil aggregation due to calcium accumulations on the exchange sites resulted in a decrease in bulk density.

An amendment that either includes soluble Ca^{2+} or dissolves Ca^{2+} upon interaction in the soil is the usual source of calcium (Rowley et al., 2018; Zhang et al., 2021). More recently, (K. Ahmed et al., 2017; Shaygan and Baumgartl, 2022), sulfuric acid (Al-Saedi et al., 2018; Gunarathne et al., 2020), and organic matter (Gunarathne et al., 2020; Shaygan and Baumgartl, 2022) have been used for reclamation of salt-affected soils.

The Abaya and Chamo Lakes region in the South Ethiopian Rift Valley is a crucial agricultural area supporting many Ethiopians' livelihoods. Unfortunately, a significant portion of the land surrounding these lakes suffers from soils, which renders them unproductive and poses a significant threat to food security. A comprehensive approach is necessary to address this challenge, including assessment, characterization, mapping, and reclamation. Understanding the extent and severity of soils is crucial to plan effective reclamation strategies. This involves assessing soil salinity, sodicity, pH, and other vital parameters across different depths and locations. Maps that depict the extent and severity of soils are essential tools for planning, resource allocation, and monitoring reclamation progress. They enable authorities to prioritize areas for immediate intervention and track the effectiveness of implemented measures. Maps empower stakeholders, including farmers, policymakers, and extension agents, to make informed land management and resource utilization decisions. Reclaiming soils brings them back into productive use, enhancing food security and improving livelihoods for local communities. The fertile lands around these lakes have the potential to yield diverse crops, feeding a large population. Reclaiming soils unlocks this potential and contributes to national

food security goals. Therefore, sufficient soil and land characteristics information is crucial for maintaining soil productivity and effective land use planning. Proper reclamation techniques can also play a significant role in restoring degraded land and improving soil quality. It is essential to prioritize sustainable land management practices to ensure the long-term health and productivity of our soil and land resources.

1.2 Objectives and Hypotheses of the Study

The general objective of the study was to assess, characterize, map, and reclaim agricultural soils around Abaya and Chamo lakes, South Ethiopian Rift Valley

The specific objectives of the study were:

1. To characterize agricultural soils around Abaya and Chamo Lakes;
2. To analyze nutrient contents and map the fertility status of the soils;
3. To determine the intensity and types of salt-affected soils and map their spatial distribution patterns;
4. To investigate the efficacy of gypsum and farmyard manure, both applied alone and in combination, in reclaiming sodic soil's chemical and physical properties.

"In line with the specific objective mentioned above, the research hypotheses were:"

1. Soils with high EC, ESP, SAR, and pH could exhibit distinct morphological, physical, and chemical properties compared to non-saline and non-sodic soils.
2. Soils could reveal deficiencies in specific plant nutrients compared to non-saline and non-sodic soils, resulting in a lower overall fertility status.
3. There would be spatial patterns in the intensity and types of soils across the study area. These patterns could be related to topography, drainage, and proximity to potential salt sources.
4. Amending sodic soil with gypsum, farmyard manure, or a combination of both would improve its chemical and physical properties compared to untreated soil. Compared to their individual effects, this improvement could be more significant with the combined application of gypsum and farmyard manure.

1.3 Descriptions of the Study Area

1.3.1 Location and climate of the study area

The Abaya-Chamo sub-basin of the South Ethiopian Rift Valley splits Ethiopia down the middle in a north-south direction. The basin comprises two lower-lying lakes, Abaya Lake and Chamo Lake (Tiruneh 2005; Walche et al. 2023). The latitude of the study area falls between $5^{\circ} 50' 00''\text{N}$ and $6^{\circ} 10' 0''\text{N}$, and the Longitude falls between $37^{\circ} 26' 0''\text{E}$ and $37^{\circ} 40' 0''\text{E}$. The altitude of the study area ranges from 1107 m around Chamo Lake to 1191 m above sea level (masl) at around Abaya Lake range. Besides, the altitude of the Institutional University Cooperation (IUC) Project area ranges from 972 masl around Abaya and Chamo lakes shores to 3464 masl in the highland mountain range (Figure 1.1). The total area of the four watersheds is 807 km²: Elgo (249 km²), Sile (227 km²), Baso (167 km²), and Shafe (164 km²). Elgo and Sile catchments drain to Lake Chamo, whereas Baso and Shafe drain to Lake Abaya. Of all Abaya-Chamo Lake watersheds, the area around two lower lying lakes, Abaya and Chamo Lakes, are selected for this specific study based on accessibility and the productive potential of the sites for crop production and they covered a total of 2019 km² area (Figure 1.1).

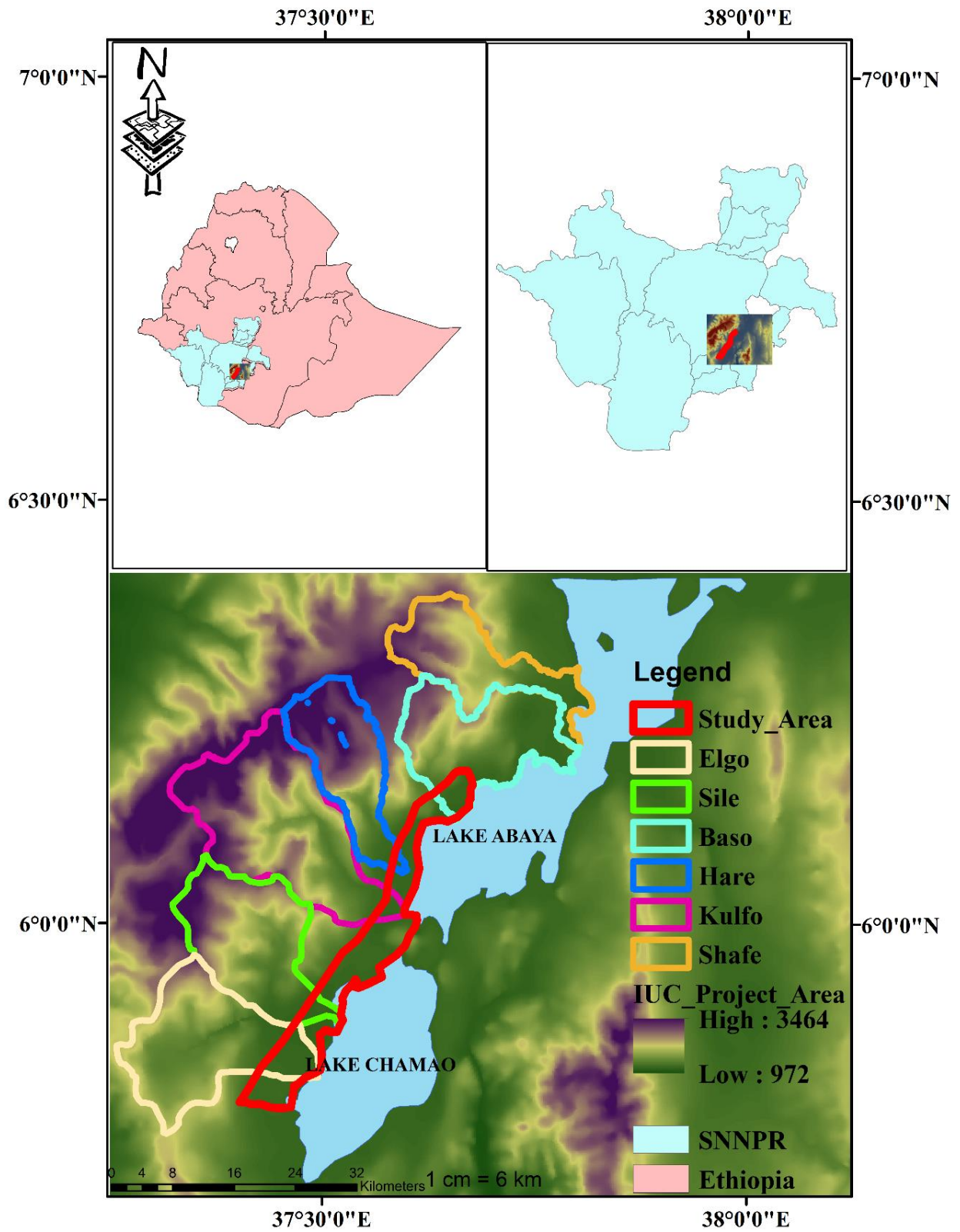


Figure 1. 1: Location map of the project area and the study sites

According to Ethiopia's major agro-ecological zone classifications, the climate of the Abaya and Chamo Lakes basin is classified as hot semi-arid lowlands (MoARD, 2005). The bimodal rainfall system in the Abaya-Chamo watersheds seems to be assisted by a humid breeze coming from the Indian Ocean, which is brought in by the inter-tropical convergence zone (ITCZ). Altitude plays a role in the distribution of rainfall. The region experiences short rains in spring (*belg*) and long rains in summer (*kremt*), resulting in a bimodal rainfall distribution in most parts of the watershed (Mengistu et al., 2019). In the study area, the rainfall peaks during April and May. On the other hand, the lowest rainfall is recorded during January and February. The temperature is high for three months in the study area. For instance, around Chamo Lake, the temperature increases in February, March, and April, while around Abaya Lakes, the temperature is high during January, February, and March. The mean annual rainfall in the area ranges from 500 to 1100 mm, and the average yearly air temperature is 17–39 °C. According to the AMU-IUC Project 4 (Appendix Table 1.1 and Figure 1.2), the mean soil temperature ranges from 22 to 35 °C.

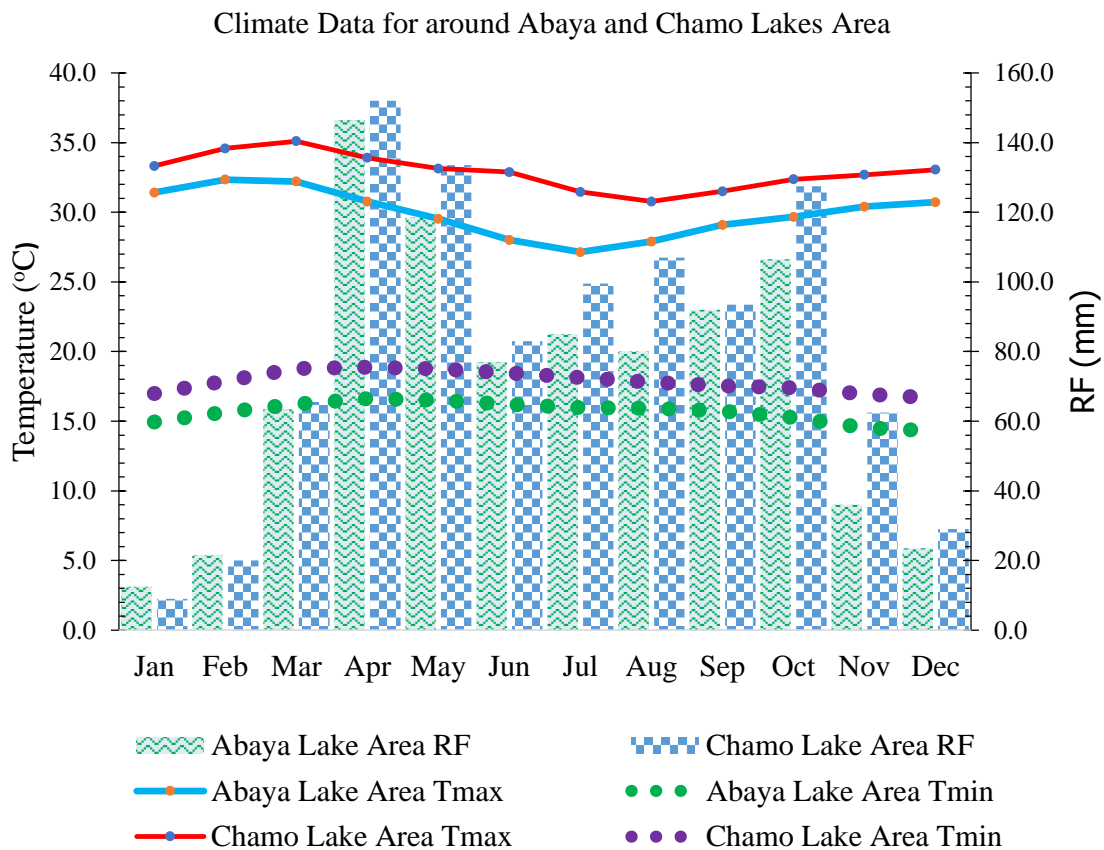


Figure 1. 2: Annual climate data around Abaya and Chamo lakes (1983–2020 average) (source: AMU-IUC project 4 meteorology station)

1.3.2 Geology, hydrology, and soils of the study area

The Pliocene and Holocene volcanic activity in the Rift Valley produced the Abaya-Chamo basin, a portion of the valley. Accordingly, ancient basement rocks are believed to lie under the whole Rift Valley (Molla and Tegaye, 2019; Philippon et al., 2014). They consist of gneisses, which transform into granites and gneissosities (Zebire et al., 2019). The geological map shows that fluvial deposit; sandy gravel mud dominated the study area (Mengistu et al., 2019; Yilma et al., 2023). Consolidated volcanic ash flows that have been converted into basalts and ignimbrites (tuffs) make up the higher strata. Thus, tertiary and quaternary volcanic rocks as well as quaternary era alluvium deposits are what primarily define the area (Dvořák, 2022; Tiruneh, 2005). The research area's geology is mostly composed of intrusive and extrusive igneous rocks, such as ignimbrite with a trachytic to rhyolitic composition (ITR), basalts, and trachyte lava flows (BTL). The floor of the rift valley is covered by lacustrine and extended Holocene fluvial deposits (fans) (Belayneh et al., 2022; Tilahun, 2022).

As observed in the shallow and deep wells, the average thickness of basalt rock's weathered and fractured zones exist at about 40 m below the surface. Because of its secondary porosity and permeability, this deposit should be viewed as a highly promising aquifer in the study area's flatlands. But ignimbrite and rhyolite-covered mountains, hillsides, and dome-shaped topography act as conduits rather than aquifers (Haji et al., 2021; Wodaje, 2017). Therefore, these mountains, hills, and domes are recharge areas for the flat lands. It is composed of varying amounts of clay, silt, sand, and gravel-sized particles, as determined in the field (Gebreegziabher et al., 2023; Wagner et al., 2018). Besides, the study area groundwater is found extensively within the lacustrine deposit surrounding the Lake. The Lake Abaya is moderately saline and alkaline, permanently brown due to fine materials being in suspension. Alluvial sediments are abundant on the floor of the rift valley near to the lakes Abaya and Chamo. Both the perennial and sporadic rivers flow into the two lakes (Daniel et al., 2022; Zekarias et al., 2021).

The presence of sufficient moisture makes soil fertility, structure, and drainage typically conducive to agricultural practices (Walche et al., 2023; Zebire et al., 2019). The reddish-gray soils on the western edge of Abaya and Chamo Lakes are classified as clay to clay loam in terms of texture (Hroch et al., 2018; Zekarias et al., 2021). The majority of soils near Abaya and Chamo Lakes were created from alluvial deposit materials (Tefferu et al., 2017). The area around Chamo Lake is characterized based on a geospatial approach by eight major soil types:

Cambisols, Fluvisols, Gleysols, Luvisols, Solonchaks, Solonetz, Vertisols, Chernozems, Kastanozems and Leptosols (Gieta 2016; Zewdu, Suryabhagavan, and Balakrishnan 2017; (Zebire et al., 2019)).

1.3.3 Population growth, settlement and land use

Around Abaya and Chamo Lakes, the population is a diverse multi-ethnic group with over 30 different languages spoken in various localities (Tiruneh, 2005). The population is 105,737 in the study area around two lakes (Tessema, 2010). Recently, there is rapid population growth and settlement (Zekarias et al., 2021). Following the population growth, the land use and degradation of the natural ecosystems are increasing, causing deforestation through increasing firewood demand, burning of shrubs and forests for livestock grazing purposes, and clearing the lands for agricultural activities (Tiruneh, 2005).

Because of the sustained dry period and shortage of soil moisture, irrigation activities by diverting water from rivers are steadily increasing in the area (Lemma and Desta, 2016). As a result, there is ever-increasing utilization of rivers for irrigation, mainly groundwater, and lakes (Hulluka et al., 2023), partially for the cultivation of banana, mango, papaya, maize, cotton, sweet potato, tomato, onion, and haricot bean around Abaya and Chamo Lakes (Walche et al., 2023).

1.4 Soil Sample Collection, Preparation, and Analysis

Five map units comprised the mapping unit used to categorize the study area. In order to examine the morphology of the soil and collect soil samples, one representative 60*60*60 cm soil sampling pit was opened in each mapping unit. Based on the standards established for agricultural salt-affected soil research by Wogi et al. (2021), composite soil samples were taken from each pit at three different soil depths (0–20, 20–40, and 40–60 cm) for soil assessment and characterization study.

In order to prepare composite soil samples from the collected soil samples, three representative soil sampling areas were chosen from each map unit and homogenized. Then, with two depths (0-20 and 20-40 cm) using a systematic sampling technique, 300 soil samples were collected, with a 600 m sampling interval, of which 100 composite soil samples were used to assess soil fertility status and mapping. The grid cell size of 200 m*200 m was made, and nine (9) composite soil samples were collected from each grid node. Each composite soil sample was collected at a 15 m radius around the center of the sampling point.

Two hundred twenty-six (226) auger soil samples were collected from 0-20 cm to assess the intensity and types of salt-affected soil and map their spatial distribution patterns. Soil samples were filled in pots and incubated for three months and leached for one month, after which samples were collected and analyzed for chemical properties. At the end of the incubation and leaching period, 48 soil samples were collected from pots using a soil corer to collect a cylindrical soil sample from the entire pot depth and analyzed for chemical properties.

Soil color was measured under uniform conditions using the Munsell Soil Color Chart (Sánchez-Marañón et al., 2005). Particle size was determined by hydrometer (Bouyoucos, 1962). The pycnometer method was used to determine the particle density (PD) (Parker et al., 2022), and bulk density (BD) was determined by the core method (Blake and Hartge, 1986). The total porosity was estimated from the determined particle and bulk densities. The moisture content at field capacity (FC) and permanent wilting point (PWP) was measured at the soil water potentials of -1/3 and -15 bars, respectively, using the pressure plate apparatus technique (Bekele and Abebo, 2019). The results were converted to volume percent (Vol %) by multiplying the gravimetric water content with the soil bulk density ratio to the water density. The available water content (AWC) was obtained by subtracting water content at PWP from FC and finally converted to mm/ m of soil depth by multiplying it by 1000.

Soil pH from saturated soil paste extract was determined using a pH meter in a 1:2.5 soil-water ratio (Rayment and Lyons, 2011). Electrical conductivity (EC) was measured from a soil saturation extract by a conductivity meter (Miller and Curtin, 2006). Organic matter (OM) was determined by the modified procedure of Walkley and Black (Dewis and Freitas, 1970). Total Nitrogen (TN) was determined by the micro-Kjeldahl method (Bremner, 1996), while available phosphorus (Av. P) was extracted and determined using the sodium bicarbonate solution following the standard procedure (Olsen, 1954).

Neutral 1N ammonium acetate extracts were used to determine the Cation Exchange Capacity (CEC) and the exchangeable bases. Sodium (Na) and potassium (K) were measured using flame photometry. Titration was used to determine the amounts of magnesium (Mg) and calcium (Ca). Derived parameters, PBS and ESP were computed as the percentage of the sum of exchangeable bases and exchangeable Na to the CEC of the soil, respectively. Using HCl, the acid neutralization method was used to measure the amount of calcium carbonate (CaCO₃). The method outlined in Handbook No. 60 was used to determine the solubility of cations and anions (Richards, 1954). Soluble calcium and magnesium were determined by Titration with

Ethylenediaminetetra-acetate (versenate) as described by (Cheng and Bray, 1955), while sodium and potassium were measured by Flame photometer from ammonium acetate, approximately 1 N. Carbonate(CO_3^{2-}) and bicarbonate (HCO_3^-) were determined by titration with acid. Chloride (Cl^-) was determined by titration with the silver nitrate method. Nitrate (NO_3^-) was determined by phenoldisulfonic acid method (Richards, 1954). Sulfate(SO_4^{2-}) contents were determined by a turbidimetric procedure using UV-Visible Spectrophotometer (Xing et al., 2020).

Sodium adsorption ratio (SAR) and Exchangeable Sodium Percentage (ESP) were calculated by the procedure outlined in Hand Book No.60 (Richards, 1954). The DTPA extractable micronutrient contents of the soils (Fe, Mn, Zn, and Cu) was analyzed by the Diethylene Triamine Penta Acetic acid (DTPA) method (Lindsay and Norvell, 1978).

1.5 Data Analysis

The soil analytical results were evaluated and interpreted following a guide to standardized analytical methodologies for soil data (Wogi et al., 2021). The outcomes of the soil study were further subjected to PCA and clustering using the statistical analysis program R-4.3.2 version (Rasheed, 2020). Additionally, connections between soil chemical characteristics were determined by computing correlation coefficients. The ordinary kriging algorithm in QGIS software was used to predict and map the un-sampled surface from laboratory point data for the fertility status, while in QGIS software was used to predict and map the un-sampled surface from laboratory point data for the intensity and types of salt-affected soil and map their spatial distributions (Takele and Iticha, 2020).

Descriptive statistics data were analyzed using SAS software, version 9.4 (Blanca Mena et al., 2017). Two way ANOVA were used to elucidate the appropriate and best amendment level to reclaim the sodic soil. Multivariate analysis (PROC COR, PROC REG, PCA, cluster) was done to differentiate appropriate or optimum treatment and to develop the best treatment level model to reclaim sodic soil (Barbudo et al., 2012)

1.6 Structure of the Dissertation

This dissertation has four article sections, preceded by a general introduction, literature review, and study area description. Each section is presented as a separate chapter, and due to the similarities between the studied factors, some repetitions were reduced. A general summary

and conclusion from the entire study follow this section. Tables and Figures are included in the dissertation.

Chapter Two

The chapter's main objective was to assess and characterize the salinity and sodicity of soil in the region around Abaya and Chamo Lakes in the South Ethiopian Rift Valley. The study was also aimed at determining the soils' physical, chemical, and morphological properties. Representative soil pits of 60*60*60 cm were examined, and samples were collected from three different depths: 0-20, 20-40, and 40-60 cm. These depths were selected based on the standards set for agricultural studies of salt-affected soil. Finally, the soil samples from each depth of the pits were analyzed to determine their properties. Cluster analysis was done to see the similarity and dissimilarity of the soil properties among the soil depth and pits.

Chapter Three

This chapter discusses the methods used to analyze nutrient contents and map the fertility status of soils. To obtain representative soil samples, the sampling method and sample quantity required for the study area were determined using information gathered from a preliminary survey and topographic map. A systematic sampling technique was used to collect 300 soil samples, with a 600 m sampling interval, but 100 composited soil samples were utilized for the study. The collected data were analyzed using descriptive and geostatistical approaches and standardized analytical methodologies for soil data.

Chapter Four

Chapter four deals with a study to determine the intensity and types of soils and map their spatial distributions. A grid soil sampling scheme was used to collect samples from agricultural soils at depths of 0-20 cm. An adequately spaced grid cell of 200 m*200 m sampling sites was generated by the QGIS software's Fishnet tool, and 226 composite soil samples were taken from each grid node. The analysis and interpretation of the data were done using both statistical and geostatistical methods. The un-sampled surface was predicted and mapped from laboratory point data using the standard Kriging algorithm in QGIS software.

Chapter Five

This chapter investigated the efficacy of amendment resources on the chemical properties of sodic soils. A factorial experiment with four levels of gypsum (0, 50, 100, and 150% GR), four levels of FYM (0, 10, 20, and 30 tons ha⁻¹), and three replications was set up using a Completely Randomized Design (CRD). Pots were incubated for three months, leached for one month, and soil samples were collected and analyzed for chemical properties. ANOVA was used to determine the best amendment level for sodic soil reclamation and multivariate analysis was done to select the optimal treatment model.

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2. CHARACTERIZATION OF SOILS AROUND ABAYA AND CHAMO LAKES, SOUTHERN ETHIOPIA RIFT VALLEY

Azmera Walche, Wassie Haile, Alemayehu Kiflu, and Dereje Tsegaye

ABSTRACT

*Soil salinity/sodicity is becoming a challenge for crop production in Ethiopia's semi-arid and arid regions. Thus, more information on soil salinity/sodicity reclamation techniques are needed for soils around Abaya and Chamo Lakes, Southern Ethiopian Rift Valley. This study was aimed to assess and characterize the morphological, physical, and chemical properties of agricultural soils. Representative soil pits of 60*60*60 cm were opened and examined. Soil samples were taken from 0-20, 20-40, and 40-60 cm depths. The soil determined properties include soil color, structure, consistence, texture, particle density, bulk density, porosity, , pH, EC, SAR, ESP, CEC, BS, OC, TN, available P, CaCO_3^- , exchangeable bases, and soluble ions (Na^+ , Ca^{2+} , Mg^{2+} , K^+ , Cl^- , SO_4^{2-} , NO_3^- , CO_3^{2-} and HCO_3^-). The analyzed soil results were rated and interpreted following a guide to standardized analysis methods. Multivariate analysis and plots were done using R software. The results revealed that the soils had considerable heterogeneity in soil morphological, physical, and chemical properties. The study site were highly alkaline (>8.5) and had very high exchangeable sodium content ($>20 \text{ cmol kg}^{-1}$), very high CEC value ($>40 \text{ cmol kg}^{-1}$), very low TN ($<0.1\%$), low levels of OC (0.5-1.5%) and exchangeable calcium (2-5 cmol kg^{-1}). The dominant soluble cation was Na^+ , followed by Mg^{2+} , Ca^{2+} , and K^+ in all soil depths of the pits. Similarly, Cl^- was dominant among the anions throughout the soil depth, followed by HCO_3^- , SO_4^{2-} , and NO_3^- . The findings of this study imply that characterizing soils in the study area around Abaya and Chamo Lakes was essential, and removing sodium and salts from the rootable soil depth may improve the soil's productivity.*

Keywords: Agricultural soils, semi-arid regions, crop production, soil properties

2.1 Introduction

Soil degradation is a major global problem in nearly all developing countries where large proportions of the population get their livelihoods directly from the soil (Tully et al., 2015). After soil erosion, soil salinity is the second largest factor in land degradation, and it has been

linked to the downfall of agricultural communities for 10,000 years (Shahid et al., 2018). Soils are distributed worldwide, and no continent is free from this problem under almost all climatic conditions (Brady and Weil, 2002; Sileshi and Kibebew, 2016). However, their distribution is relatively more extensive in the arid and semi-arid regions than in the humid regions. Especially in arid and semi-arid regions, soils often occur on irrigated lands, where annual rainfall is insufficient to meet plants' evaporation needs and salts' leaching (Sileshi and Kibebew, 2016).

The sources of salts append saline parent materials, extreme weathering of rocks and primary minerals, fossil salts of retired marine and lacustrine deposits, atmospheric deposition, a troupe of saline sediments in catchment areas, irrigation waters, and fertilization (Levy et al., 2005). Irrigation water or fertilization may also introduce salts in the arable lands (Sileshi and Kibebew, 2016). A large land area is becoming unproductive yearly because of salinity and sodicity. Soil salinization is a growing issue whenever irrigation is used as a result of the reliance on rainfed agriculture, especially in arid and semi-arid regions. Soil degradation due to salinity and sodicity is increasing at an alarming rate endangering the environment, agricultural ecosystems, and human life (Ali et al., 2008). About 10-20% yield loss can occur due to salinity for many crops, which may prevent cropping altogether when severe and lead to desertification (Shahid et al., 2018).

Globally, a total land area of 1 billion hectares is salt-affected (FAO, 2020), and nearly 2,000 ha of agricultural land is lost from production every day because of salinization (Shahid et al., 2018). Different African nations are affected by salt to varying degrees, including Kenya (8.2 million hectares), Nigeria (5.6 million hectares), Sudan (4.8 million hectares), Tunisia (1.8 million hectares), Tanzania (1.7 million hectares), and Ghana (0.79 million hectares) (Bellido-Jiménez et al., 2021). In Ethiopia, it was reported that there are over 11 million ha of unproductive, naturally salt-affected soils and the country ranked first in Africa (Abegaze et al., 2006; Berhane and Chala, 2017; Kidane et al., 2006). With this, 44 million ha is prominently susceptible to salinity problems (Gebremeskel et al., 2018). In the country, the natural salt-affected areas are found in the arid and semi-arid lowlands and in Rift Valley areas, which have higher evapotranspiration rates when compared to precipitation (Daba and Qureshi, 2021; Farifteh et al., 2006) The Rift Valley, the Denakil Plains, the Wabi Shebelle River Basin, and the lowlands irrigated regions of Ethiopia have these salt-affected zones (Habtamu and Wassie, 2022; Levy et al., 2005) The development of large-scale irrigation projects and the lack of proper drainage systems in the Rift Valley are increasing because of export crop

production. Due to this, salinity resulted in increasing severity and rapid expansion of soil salinity and sodicity problems in the Ethiopia Rift Valley area. Consequently, the problem leads to a loss of land for crop cultivation in these areas (Asad et al., 2018).

When plants grow under saline conditions, they are subjected to three types of stress; water stress caused by the osmotic pressure, mineral toxicity stress caused by the salt, and disturbances in the balance of minerals (Ahmed and Ahmed, 2007). Salinity becomes problematic when enough salts accumulate in the root zone to affect plant growth negatively. In the root zone from the surrounding soil, excess salts hinder plant roots from withdrawing water. In this regard, it lowers the amount of water available to the plant (Akhtar, 2003). This problem harms soil fertility, and thereby reducing soil productivity (Farifteh et al., 2006). Additionally, issues with water infiltration, air movement, root penetration, and seedling emergence are caused by the changing of soil physical qualities caused by the swelling and dispersion of colloidal soil particles brought by an excess of exchangeable Na (Pearson, 2004). Finding solutions to these problems requires identifying the currently geo-referenced soil fertility status (Negassa and Gebrekidan, 2003), the chemical and physical nature of the soil that induces the problem of soils (Rengasamy, 2010), and irrigation water management systems (Tessema et al., 2023). Due to the need for more quality irrigation water to satisfy the water requirement of all crops grown in these arid and semi-arid regions, farmers are forced to use all irrigation water sources of any quality. This practice often led to the gradual development of soils. Hence, knowledge of the kinds and properties of soils and irrigation water quality is critical for decision-making concerning soil management and crop production (Adane et al., 2015; Rehman et al., 2002). Land degradation due to poor land management practices pursues without any reduction. Farmers' output and productivity are thus falling. This falling in production and productivity endangers the food and nutrition security of the community (Fekadu et al., 2018).

In some respects, addressing sodicity/salinity-induced soil degradation constantly improved soil, water, and crop management practices is essential for achieving food security and avoiding desertification (Shahid et al., 2018). Furthermore, the prevailing land use system and management interventions must be held up by information showing the potential and constraints of soil resources (Fekadu et al., 2018).

Generally, few studies have been carried out on assessing and characterizing the properties of agricultural salt-affected soil in Ethiopia,, particularly around Abaya and Chamo Lakes South

Ethiopia Rift Valley. This information helps monitor the success of reclamation efforts and adjust the plan as needed. Reclaiming salt-affected soil can improve productivity and food security and reduce water use. It also enhances soil health, increasing crop yields by 50% (Tessema et al., 2023) and reducing pest and disease problems by creating a healthier environment for plants. Knowledge gaps exist in the study area in management of the potential agricultural soils. This study will investigate to fill the knowledge gap and give direction on managing agricultural soils since the area is prone to soil sodicity/salinity. Since the nature and characteristics of these soils vary, they also require unique approaches in reclamation and management to maintain production. Therefore, this study was initiated to characterize the extent, nature, and distribution of salts in agricultural soils along the soil depths in the Southern Ethiopian Rift Valley.

2.2 Materials and Methods

2.2.1 Soil sampling, sample preparation and laboratory analysis

The terrain features such as elevation, slope, aspect, and curvature are similar in the study area (Table 2.2 and Appendix Figure 2.1). Hence, based on the data obtained from the preliminary soil survey through a salinity and sodicity indicator-based approach and visual observation regarding the presence of white salt crust and the black hardened upper layers, the soils around Abaya and Chamo Lakes were subsequently assessed and characterized (Appendix Figure 2.2). Since the study area is within the same elevation range, we classified mapping units based on areas with similar drainage characteristics and potential for salt accumulation. In addition, we also considered the soil type, vegetation cover, and land use history of the study area. The physicochemical properties of soils around the pits were determined by collecting 15 surface soil samples to determine each representative pit. The physiochemical properties of the surface soil samples were similar to that of the surface pits depths confirming that the right representative pits were opened to characterize the soils around Abaya and Chamo Lakes in southern Ethiopia Rift Valley (Appendix Table 2.2).

Accordingly, the study area was classified into five (5) different map units. From each map unit, one representative soil sampling pit of 60*60*60 cm size was opened for soil morphological examination and soil sample collection. Then, a total of 15 soil samples were collected from three soil depths (0-20, 20-40, and 40-60 cm) based on the criteria set for studying agricultural soils by Wogi et al. (2021). After cleaning loose debris from the pit face, color, texture, consistency, structure, plant rooting patterns, and other soil features were

described following the Guidelines for Soil Description (FAO, 2006). Soil color was measured under uniform conditions using the Munsell Soil Color Chart (Sánchez-Marañón et al., 2005). Particle size distribution was determined by hydrometer (Bouyoucos, 1962). The pycnometer method was used to determine the particle density (PD) (Parker et al., 2022). Bulk density (BD) was determined by the core method (Blake and Hartge, 1986). The total porosity was estimated from the determined particle and bulk densities.

Soil pH was determined from saturated soil paste extract using a pH meter in a 1:2:5 soil-water ratio (Rayment and Lyons, 2011). Electrical conductivity (EC) was measured from a soil saturation extract by a conductivity meter (Miller and Curtin, 2006). Organic matter (OM) was determined by the modified procedure of Walkley and Black (Dewis and Freitas, 1970). Neutral 1N ammonium acetate extracts at pH 7.0 solution was used to determine the Cation Exchange Capacity (CEC) and the exchangeable bases. Sodium (Na) and potassium (K) contents were measured using flame photometry. Titration was used to determine the amounts of magnesium (Mg) and calcium (Ca). Using HCl, the acid neutralization method was used to measure the amount of calcium carbonate (CaCO₃). Total nitrogen (TN) was determined by the micro-Kjeldahl method (Bremner, 1996), while available phosphorus (Av. P) was extracted and determined using the sodium bicarbonate solution following the standard procedure (Olsen, 1954). The method outlined in Handbook No. 60 was used to determine the solubility of cations and anions (Richards, 1954).

Soluble calcium and magnesium were determined by Titration with Ethylenediaminetetraacetate (versenate) as described by Cheng and Bray (1955), while sodium and potassium were measured by Flame photometer from ammonium acetate extract (approximately 1 N). Carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻) were determined by titration with acid. Chloride (Cl⁻) was determined by titration with the silver nitrate method. Nitrate (NO₃⁻) was determined by phenoldisulfonic acid method (Richards, 1954). Sulfate (SO₄²⁻) contents were determined by a turbidimetric procedure using UV-Visible Spectrophotometer (Xing et al., 2020). All soil samples were analyzed for critical salinity and sodicity parameters. Sodium adsorption ratio (SAR) and Exchangeable Sodium Percentage (ESP) were calculated by the procedure outlined by Richards (1954).

$$SAR = \frac{Na^+}{\left(\frac{Ca^{2+}+Mg^{2+}}{2}\right)^{\frac{1}{2}}} \dots\dots\dots (1)$$

$$ESP = (100(-0.0126 + 0.01475(SAR)))/1 + (-0.0126 + 0.01475(SAR))\dots\dots (2)$$

Soils in the research region were assessed and divided into different salt-affected soil classes (sodic and non-saline non-sodic soils) according to the standards established by the USSLS, shown in Table 2.1(FAO, 2020). Licensed a geostatistical analyst extension tool in Arc GIS 10.81 software was used to produce maps of soils of the study area.

Table 2. 1: Guideline for classification of salt-affected soils

Classification	EC of saturation extracts (ECe) at 25 °c (mmhos/cm)	Exchangeable Na percentage (ESP)	pH (H ₂ O)	Soil physical condition
Saline	> 4	< 15	< 8.5	Normal
Sodic (Alkali)	< 4	> 15	> 8.5	Very poor
Saline sodic	> 4	> 15	< 8.5	Normal
Non-saline non-sodic	< 4	< 15	≈ 7.0	Normal

Source: (FAO, 2020).

2.2.2 Data Analysis

Following a guide to standardize analytical methodologies for soil data, the results of the soil analysis were evaluated and interpreted. The outcomes of the soil study were further subjected to PCA, and clustering using the statistical analysis program R. Additionally, associations between soil chemical characteristics were determined by computing Pearson correlation coefficients.

2.3 Results and Discussion

2.3.1 Site characteristics of representative pits

According to the site characteristics of the study locations, the slope, degree of water erosion, parent material and land use were similar (Table 2.2). Pits AL01, AL02, and AL03 were around Abaya Lake; whereas Pits CL01 and CL02 were close to Chamo Lake. Five separate pits represented the flat area in the study site; based on their slope gradient (2%), the area is flat and known for its alkaline environment. The area around the pit is grassland used for animal husbandry, and it is bare land. Almost all of the study area had poor drainage, and are formed from lacustrine and sedimentary Colluvium deposits.

Table 2. 2: Site and physiographic characteristics of the representative soil pits

Parameters		Around Chamo Lake		Around Abaya Lake		
		Pit, CL01	Pit, CL02	Pit, AL01	Pit, AL02	Pit, AL03
Cordinate ^a	Latitude	584129	584140	606999	612708	616202
	Longitude	3745538	3745538	3757727	3763443	3766494
	Altitude (masl)	1107	1128	1191	1184	1183
	Slope (%)	2	2	2	2	2
	Slope Position	Bottom (flat)	Bottom (flat)	Bottom (flat)	Bottom (flat)	Bottom (flat)
	Drainage Class	Imperfectly drained	Poorly drained	Poorly drained	Poorly drained	Poorly drained
	Erosion/Deposition	N ^c	N	N	N	N
	Parent material	Colluvium sedimentary	Colluvium sedimentary	Colluvium sedimentary	Colluvium sedimentary	Colluvium sedimentary
	Land Use	Animal Husbandry	Animal Husbandry	Animal Husbandry	Animal Husbandry	Animal Husbandry

^aUTM coordinate, Zone 37 N, datum WGS 1984. ^cNo evidence of erosion

2.3.2 Morphological properties of the soils in the pits

The soils in the pits were very dark grayish brown (10YR 3/2) to brown (7.5YR 4/3) in color (moist) at the surface depth (0-20 cm); Black (10YR 2/1) to very dark brown (7.5YR 2.5/2) in the subsurface depth (20-40 cm); and very dark brown (10YR 2/2) to brown (7.5YR 4/3) at 40-60 cm depth (Table 2.3). A brownish to black soil color of the studied soils could be due to the dispersion of soil organic matter and humic substances by sodium. Historically, sodic soils were often called black alkali soils due to the dispersion and dissolution of humic substances resulting in a dark color (Rashad et al., 2022). The color of the soil is a crucial characteristic that can be used to determine the degree of mineral weathering, the amount of organic matter, and the soil's aeration (Sharma et al., 2006).

The soil structure was angular blocky in the surface depth (0-20 cm) and sub-angular blocky in the rest of the soil depth. The blocky structure of soils could be due to higher clay content and low organic matter than the subsurface layers. It can be divided into two categories: subangular blocky, which has more rounded corners, and angular blocky which has sharp angles most commonly found in higher-clay soils (Sedov et al., 2010). Consistence (dry) is hard in the surface depth (0-20 cm) and slightly hard in the subsurface depth (20-60 cm). Both surface and subsurface depth are sticky and plastic (wet)., The consistence was friable (moist) in almost throughout the soil depth. Although consistence is an inherent soil characteristic, high OM in the surface layer could change the consistence (Wakene and Heluf, 2004).

Root abundance ranged from none (< 2 mm) to very few (1-20 mm) (Table 2.3). It could be due to the net effect of sodicity and salinity. The combined effect of salinity and sodicity can particularly harm plant roots (Stavi et al., 2021). High salt concentrations can further

exacerbate the adverse effects of sodicity, creating compacted soil and a harsh environment for root development and function (Mohanaavelu et al., 2021). The findings of Srivastava et al. (2014) indicated that salt stress induces changes in soil physical properties limiting root growth in soils.

Table 2. 3: Morphological characteristics of the soils in the pits

		Around Chamo Lake						Around Abaya Lake								
		Pit, CL01			Pit, CL02			Pit, AL01			Pit, AL02			Pit, AL03		
		Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)		
Parameters		0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
Color	Moist	7.5YR 4/3	7.5YR 2.5/2	7.5YR 4/3	10YR 2/2	10YR3 /3	10YR3 /2	10YR 3/1	10YR 2/1	10YR 4/3	10YR 3/2	10YR 2/2	10YR 4/2	10YR 3/2	10YR 3/2	10YR 2/2
Structure ^a	Grade, Size, and Type	ST, VF, AB	MO, FI, SB	MO, FI, AB	ST, ME, AB	MO, ME, SB	MO, ME, SB	MO, FI GR	ST, ME, AB	WE, FI, GR	MO, ME, SB	MO,M E, SB	MO, ME, SB	ST, ME, AB	MO, FI, SB	MO, FI, SB
Consistence ^b	Dry	HA	SO	SHA	HA	SHA	SHA	HA	SHA	SHA	SHA	SHA	SHA	SHA	SHA	SHA
	Moist	VFI	LO	FR	FR	FR	FR	VFR	FR	FR	FR	FR	FR	FR	FI	FR
Texture ^c	Wet	ST, VPL	NST, NPL	VST, VP	ST, PL	VST, PL	VST, VPL	ST, VPL	VST, VPL	VST, VPL	ST, PL	ST, PL	ST, PL	ST, PL	VST, VPL	ST, PL
	Feel	SCL	SL	SL	C	C	C	C	CL	C	C	CL	CL	CL	C	C
Roots ^d	Size and abundance	VF, V	VF, V	VF, N	VF, N	VF, N	VF, N	VF, V	N, N	N, N	M, C	F, V	F, V	VF, V	N, N	N, N

^aGR: granular, AB: angular blocky, SB: subangular blocky, VF: Very fine, FI: fine, ME: medium, , and ST: strong, MO: moderate, WE: weak

^bFI: firm, VFI: Very firm; FR: friable, VFR: very friable HA: hard, SHA: slightly hard LO: loose, SO: soft, ST: Sticky, VST: Very sticky, NST: nonsticky, PL: plastic, VPL: Very plastic, NPL: nonplastic, , , , and. ^cC: clay, CL: clay loam, and SCL: silty clay loam. ^dF: fine, N: none, V: very few, and VF: very fine

2.3.3 Physical properties of the soils in the pits

Soil texture is clay loam and clay for the CL01 and CL02 pits, respectively, while it was clay, clay, and sandy clay for the AL01, AL02, and AL03 pits, respectively. The result revealed that there is some textural variation among the studied pits. Textural variations can help explore soil genesis by providing clues about the parent material and influencing soil formation rate and nutrient availability. Sandy soils are formed from more slowly weathering parent material due to their smaller surface area and weathering process. Clayey soils have a higher nutrient content due to their larger surface area and complex bonding with nutrients, making them more accessible to plants (Kome et al., 2019).

Soil texture in both surface and subsurface had silt-to-clay ratios greater than 0.3 indicating that the soils are young (Table 2.4). Young parent materials usually have a silt/clay ratio above 0.15 (Sharu et al., 2013). These results indicated that the soils around Abaya and Chamo Lakes are relatively young with a high degree of weathering potential. Similar results have been reported for other soils of similar ecological settings (Kalala et al., 2017; Kebeney et al., 2014).

The mean bulk density of the soils around Abaya and Chamo Lakes was 1.35 g cm^{-3} varying from 1.2 to 1.52 g cm^{-3} on the surface layers (0-20 cm), and from 1.18 to 1.55 g cm^{-3} in the 20-40 cm, and from 1.17 to 1.44 g cm^{-3} in the depth of 40-60 cm (Table 2.4). The increased trend in bulk density was observed in the sodic soils of CL01, CL02, and AL03 pits. This high bulk density in the surface of sodic soils could be due to the high accumulation of exchangeable sodium on the surface soil. This high accumulation of exchangeable sodium makes the compaction and dispersion of soil structure corroborating Gangwar et al. (2020). Similarly, soil compaction occurs when a force is applied more than the soil's resistance to deformation due to having a high amount of sodium in the sodic soil and a high traffic load and of grazing animals (Taghizadehghasab et al., 2021).

On the other hand, the bulk densities of the soils in the non-saline non-sodic pits (AL01 and AL02) increased with depth. Lower bulk densities in the surface layers of these pits could be due to organic matter content that was relatively higher in the surface depth (0-20 cm) as compared to the subsurface depths (20-40, 40-60 cm), contributing to porous and well-aggregated structure, and thereby lowering bulk densities (Appendix Table 2.1.) (Alemayehu et al., 2016). Similarly, Zebire et al. (2019) reported a bulk density of 1.5 gm cm^{-3} in Sile-sego watershed around Chamo Lake. Generally, the bulk density of 1.35 gm cm^{-3} in soils around Abaya and Chamo Lakes could be rated as good range in accordance with the critical value of

bulk density (Landon, 2014), whereby the optimum bulk density value for plant growth at limited root penetration is 1.4 g cm^{-3} for clay soils (Massawe et al., 2017). The particle density of the soils in most depths of the pits (CL01, CL02, and AL01) was almost similar to the average values for mineral soils (2.65 g cm^{-3}), indicated by Brady and Weil (2002), whereas that of the soils in AL02 and AL03 pits were above the average value for mineral soils worldwide (Table 2.4).

In the study area, the total porosity of the soil decreased with depth for all soil pits. Total porosity ranged from 39% in pit CL01 to 61% in pit AL02 of the surface soil depth (0-20 cm). On the other hand, it varied from 27% in CL01 pit to 59% in in the subsurface soil depth (20-40, 40-60 cm) of AL02 pit.

2.3.4 Chemical properties of the soils in the pits

The CEC of the soils ranged from 40.9 to 64.9 cmolc kg^{-1} (Table 2.4). The relatively high CEC of the soils in the study area suggests that they are fertile and capable of supporting an extensive variety of plant growth (Bonanomi et al., 2020). The type of soil, the amount of clay and organic matter in the soil, and the pH of the soil have impacts on the CEC of the soil (Murphy, 2015). Because clay particles have a larger surface area that can bind more cations, they have a higher CEC than sand-based soils. Soils with high levels of organic matter will also have high levels of CEC, as organic matter has high CEC (Kaiser et al., 2008).

The CEC is additionally affected by the pH of the soil. The CEC is higher in alkaline than acidic soils (Chen et al., 2020). There are fewer H^+ ions in alkaline soils, so the clay minerals and organic matter can hold more cations and hence give the soils a higher CEC (Sparks et al., 2022). According to Wogi et al. (2021), the CEC of the studied soils is above the very high range ($>40 \text{ cmolc kg}^{-1}$) both in surface (0-20 cm) and sub-surface (20-40 and 40-60 cm) depths, indicating that the soils could be made productive by reclamation. The very high CEC in the study soils could be due to presence of more weatherable primary minerals which could be regarded as a plant nutrient reserve (da Silva et al., 2022). Thus, such soils are considered capable of good production, if other factors are favorable (Mulat et al., 2018). Similarly, the total nutrient fixing capacity of the soils is well expressed by its Cation Exchange Capacity, and values over 10 cmol kg^{-1} are considered satisfactory for most crops (FAO and ISRIC, 2012). Accordingly, these soils have a well-buffering capacity for changes in chemical properties as the minimum value is $40.9 \text{ cmolc kg}^{-1}$ both at surface and sub-subsurface depths (Oliver et al., 2013).

The available phosphorus content of the soils in the surface (0-20 cm) soil depth of the majority of pits was very high in accordance with Wogi et al. (2021) who rated available P content $>25 \text{ mg kg}^{-1}$ very high, 18 to 25 mg kg^{-1} high (Table 2.4). However, the P content in the surface layer of the AL02 pit (Lante site) could be rated as low. The available P concentrations in the subsurface depths (20-40, and 40-60 cm) of the pits were irregular. In the surface layers, phosphorus from organic matter might have been released due to increased susceptibility of the soils to weathering and decomposition. . Since the material was a recent deposit, the top soil layer has more phosphorus than its parent material (Alemayehu, 2018; Vitousek et al., 2010). The effect of soil alkaline phosphatase activity on soil available phosphorus may be explained by an increase in the ratio of medium and active inorganic phosphorus in the soil phosphorus pool (Xie et al., 2022).

The organic carbon (OC) concentration in the soils is rated as very low to low in accordance with Wogi et al. (2021), who rated OC content < 0.5 very low and 0.5 to 1.5 low. The absence of good soil biological conditions in the research area might be the reason for the reduced amount of organic matter (OM) (Seid and Genanew, 2013). However, the low organic carbon could be due to the rapid decomposition of organic matter in semi-arid climatic conditions (Kumar et al., 2018) and hindering the accumulation of organic carbon in the soil and the content consistently decreases with increasing soil depth (Appendix Table 2.1) (Amini et al., 2016).

The total nitrogen both in the surface and subsurface depths are rated as very low (Landon, 2014). The trend in total nitrogen distribution within the pits was not similar to that of OC, implying that the organic matter was not the primary source of total nitrogen in the study soils. Even within specific environments, there seems to be no general agreement on ratings of N values measured by the same method (Landon, 2014), and the ratings of total nitrogen are given as a very general reference to total N content for Ethiopian soils (Wogi et al., 2021) . In contrast, Asmamaw et al. (2018) reported a strong correlation between total N and organic carbon, stating that the variation in total nitrogen content is related to variation in organic carbon in soils of the North-Eastern Rift Valley of Ethiopia.

The soils in most pits had 2–3.8% CaCO_3 content throughout the soil depth, which could be rated as low CaCO_3 content (Table 2.4), and physically less visible effervescences of calcaric soil material. At the same time, surface soil (0-20 cm) of Pit AL02 and subsurface soil (40-60 cm) of Pits CL01, CL02, and AL01 had $<2\%$ CaCO_3 which was rated none to very low by

FAO and ISRIC (2012). One possible explanation for this low CaCO_3 level is precipitation mixed with bicarbonate ions from conditions that inhibit the reaction between calcium and bicarbonate ions. Another possible reason could be high soil pH. CaCO_3 precipitates in soil pH around 8.5. Hence, the pH is higher than 8.5; for the pits CL01, CL02, and AL01, the precipitation of CaCO_3 could be low (Table 2.5). The CaCO_3 variation may be ascribed to the parent the nature of the material and the irrigation water quality (Rezapour et al., 2013). A smaller amount of calcium carbonate enhances soil structure and is essential for productivity of soils. However, higher concentrations may create iron deficiency and, when cemented, reduce the water storage capacity of the soils (FAO and ISRIC, 2012).

Table 2. 4: Physical and chemical properties of the soils

Parameters		Around Chamo Lake						Around Abaya Lake								
		Pit, CL01			Pit, CL02			Pit, AL01			Pit, AL02			Pit, AL03		
		Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)		
		0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
Particle size analysis (%)	sand	14.00	56.00	60.00	18.00	2.00	8.00	28.00	24.00	38.00	62.00	8.00	20.00	56.00	52.00	54.00
	Silt	52.00	16.00	16.00	20.00	32.00	26.00	26.00	28.00	26.00	10.00	32.00	48.00	10.00	10.00	4.00
	Clay	34.00	28.00	24.00	62.00	66.00	66.00	46.00	48.00	36.00	28.00	60.00	32.00	34.00	38.00	42.00
Textural class		Silty clay loam	Sandy clay loam	Sandy clay loam	Heavy clay	Heavy clay	Heavy clay	Clay	Clay	clay loam	Sandy clay loam	Clay	silt clay loam	Sandy clay loam	Sandy clay	sandy clay
Silt/Clay		1.50	0.60	0.70	0.30	0.50	0.40	0.60	0.60	0.70	0.40	0.50	1.50	0.30	0.30	0.10
BD (g cm ⁻³)		1.52	1.22	1.17	1.40	1.18	1.41	1.34	1.39	1.29	1.20	1.37	1.33	1.52	1.55	1.44
PD (g cm ⁻³)		2.50	1.70	2.00	2.50	2.50	2.50	2.40	2.50	2.50	3.10	3.30	2.50	3.30	3.10	2.40
Porosity (%)		39.00	27.00	41.00	44.00	41.00	29.00	44.00	45.00	49.00	61.00	59.00	47.00	54.00	50.00	40.00
CEC (cmolc kg ⁻¹)		44.80	46.30	43.30	64.90	52.20	55.90	48.90	44.30	40.90	47.40	46.60	41.10	48.20	46.10	49.40
BS (%)		151.00	131.00	135.00	153.00	131.00	106.00	101.00	85.00	71.00	74.00	91.00	145.00	82.00	113.00	88.00
Av.P (mg kg ⁻¹)		42.05	13.78	8.56	77.29	78.98	23.39	29.52	31.43	8.28	5.64	2.38	21.37	44.58	24.07	19.4
OC (%)		0.78	0.28	0.21	1.88	0.91	0.97	1.43	0.53	0.36	0.81	0.51	0.61	0.68	0.42	0.46
TN (%)		0.06	0.06	0.04	0.03	0.05	0.04	0.06	0.05	0.07	0.06	0.06	0.09	0.04	0.06	0.06
CaCO ₃ (%)		3.80	2.20	1.50	2.30	2.00	1.20	2.80	2.20	0.10	1.10	2.40	2.40	2.80	2.70	2.40

2.3.5 Soil reaction, electric conductivity, exchangeable bases, and exchangeable sodium percentage of the soils

According to Wogi et al. (2021), the soil reaction was highly alkaline throughout the CL01, CL02, and AL03 pits ranging from a value of 9.4 at the sub-surface depth (40-60 cm) of pit AL03 to 10.3 in the surface depth (0-20 cm) of pits CL01 and AL03 (Table 2.5). On the other hand, the soil pH values in pits AL01 and AL02 were mildly alkaline to highly alkaline and ranged from a value of 7.7 at the surface depth (0-20 cm) of pit AL02 to 9.8 sub-surface depth (20-40) of pit AL02 (Table 2.5). This can be attributed to the low leaching of bases in clay soils (Landon, 2014; Mukungurutse et al., 2018), typical in pits CL01, CL02, and AL03. Soil reaction generally revealed a decreasing trend with the soil depths in the pits.

The soil was rated non-saline with an electrical conductivity ranging from 0.67 dS m⁻¹ at the subsurface depth (40-60 cm) of pit AL02 to 8.21 dS m⁻¹, whereas it was strongly saline in the surface depth (0-20 cm) of pit CL02 (FAO 2020). The ECe of the soils in pits AL01 and AL02 is rated as slightly saline for indicating it is suitable for crop production compared to pits CL01, CL02, and AL03. The pH and EC values indicate that the soils of the study area are non-saline non sodic for pits AL01 and AL02, whereas they indicate sodicity for pits CL01, CL02, and AL03 in accordance with the rating of FAO (2020). There were regular patterns of EC and pH values with depth (Appendix Table 2.1).

The exchange complex of the soils was dominated by Na, followed by Mg, K, and Ca. Exchangeable Na ranged from 33.27 to 93.68 cmol(+) kg⁻¹ and was categorized as very high according to Wogi et al. (2021) (Table 2.5). Consequently, most of the pit's ESP values were higher than 15%, which is usually taken as the critical limit for classification as a sodic soil (Brady and Weil, 2002), and the highest value was recorded in pit CL02 (around Chamo Lake) (Table 2.5).

The high sodium content and low calcium and magnesium contents were due to low precipitation, and such a reaction is enhanced under the semi-arid climatic condition with the low partial pressure of CO₂; and low content of organic matter in the soil might have been the reason for high ESP values as reported by Kumar et al. (2018). The soils' relatively medium and heavier texture, soil erosion, and low lying area with poor drainage might also be the probable reasons for the high ESP (Shirgire et al., 2015). Thus, reclamation measures to remove excess Na through the application of gypsum followed by leaching should be employed for successful crop production at site (pit CL01, CL02, and AL03); while the rest of pits (AL01

and AL02) require leaching with good quality irrigation water and recommended integrated soil management practice (Ezeaku, 2015; Gangwar et al., 2020). Exchangeable Mg and K were found to be in the medium to the high amount (Wogi et al., 2021). The calcium content was in the very low to low (<2 to $2-5$ $\text{cmol}(+) \text{kg}^{-1}$) for pits CL01, CL02, and AL03, while it was in the medium to very high range ($5-10$ to >20 $\text{cmol}(+) \text{kg}^{-1}$) for pits AL01 and AL02.

2.3.6 Agricultural Salt-affected classes of the soils

Based on agricultural arable land soil depth of 0-20 cm and 20-40 cm, Pit CL01 and pit CL02 (around Chamo Lake), and Pit AL03 (around Abaya Lake) were categorized as sodic soil according to FAO (2020). In contrast, pits AL01 and AL02 (around Abaya Lake) were categorized as non-saline non-sodic soil having $\text{EC}<4$, $\text{SAR}<13$, and $\text{ESP}< 15$. The investigated soil attributes provided hints and recommendations for applying soil reclamation techniques in the region, based on pit-based detail investigation. However, it needs, further study on agricultural salt-affected soil mapping regarding salt type and intensity of salt problems. Thus, the soils of pits CL01, CL02, and AL03 need calcium-rich amendment material plus leaching by good quality irrigation water. Pits AL01 and AL02 need leaching through good quality irrigation water and amendments (chemical amendments/gypsum, organic amendments/farm yard manure, compost, biochar/ and halophyte plants since they have vulnerability to salinity even if the soil was categorized non-saline non-sodic (Figure 2.1). Reclamation methods for saline and non-saline soils depend on texture, salt composition, drainage, leaching, amendments, and crop selection. Leaching removes salts, while amendments improve soil structure and reduce salt concentration.

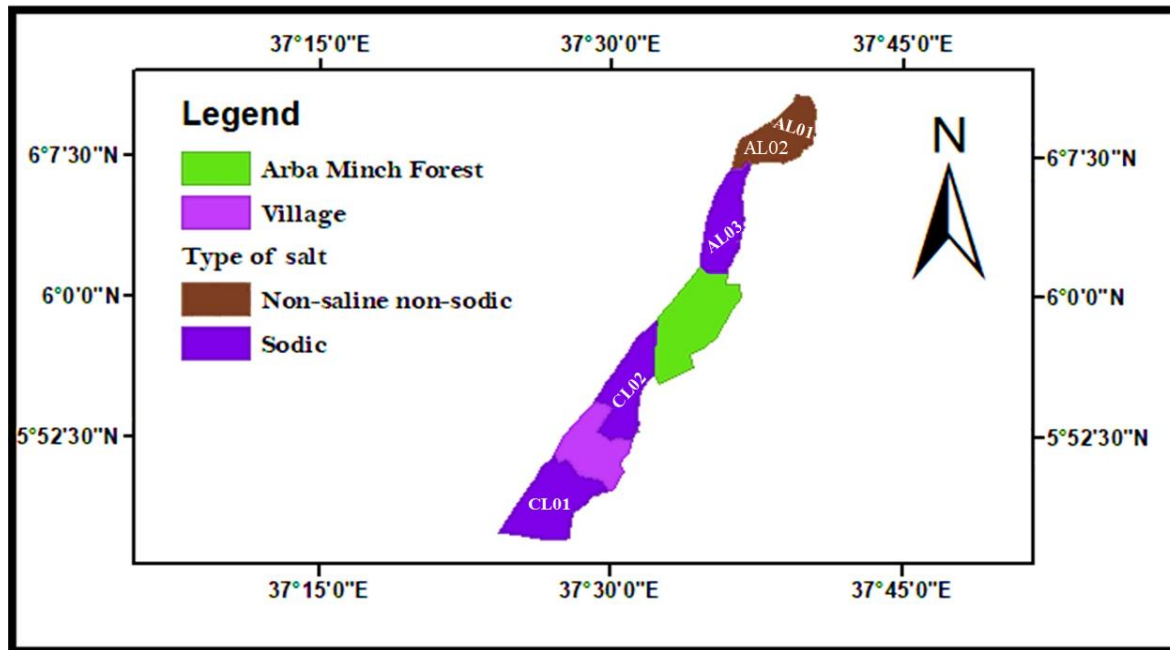


Figure 2. 1: Salt-affected soil classes for pits with depth (cm) wise (where: CL01 and CL02 are pits around Chamo Lake and AL01, AL02 and AL03 are pits around Abaya Lake)

2.3.7 Soluble chemical properties of the soils

Sodium was the dominant soluble cation, followed by magnesium, calcium, and potassium in decreasing order in all soil depths of the pits. Soluble Na^+ in the five pits revealed dominance across different depths, in which depths 0-20 cm gave higher values over 20 – 40 cm and 40 – 60 cm depths, but no significant difference was found between 20 – 40 cm and 40 – 60 cm depths. The soluble Na^+ content of the soils consistently decreased with an increase in soil depth (Table 2.5). It could be due to the moving of soluble Ca and exchangeable Ca to soil depth by leaching, displacing the exchangeable and soluble sodium. This is aligned with the findings that showed soluble Na^+ increases from bottom to top of the soil depth (Salih and Elsheik, 2014). This result indicated a similarity to that soluble Na^+ leached from the upper layer to the lower ones, as mentioned by Gardner et al. (1959). Also, this pattern was attributed to the decreasing $\text{Ca}^{2+} : \text{Na}^+$ ratio in the soil solution as it moved down the soil depth displacing exchangeable Na^+ , as mentioned by Hussain et al. (2001).

Among the anions, Cl^- was dominant throughout the soil depth, followed by HCO_3^- and SO_4^{2-} (Table 2.5). These anions consistently increased with depth in line with soluble Na^+ . Most researchers reported that the solution's common soluble cations associated with soil salinity are Na^+ , Ca^{2+} , and Mg^{2+} , while the common anions are Cl^- , SO_4^{2-} , and HCO_3^- (Eshete, 2022; FAO,

2020). In all the soil depths of the pits, CO_3^{2-} was absent. Among the cations and anions, Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , and HCO_3^- were in higher concentrations throughout the pit depth-wise. Hence, chloride and sulfate salts of sodium and calcium were the major salts contributing to the salinity and sodicity development of the soils around Abaya and Chamo Lakes in south Ethiopian rift valley.

Table 2. 5: Soil reaction, electric conductivity, exchangeable bases (cmolckg⁻¹), sodium adsorption ratio, exchangeable sodium percentages, and soluble soluble chemical properties (milliequivalents per liter/meql⁻¹) of the experimental soils.

Parameters	Around Chamo Lake						Around Abaya Lake								
	Pit, CL01			Pit, CL02			Pit, AL01			Pit, AL02			Pit, AL03		
	Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)		
	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
pH	10.30	9.90	9.60	10.30	9.70	9.40	9.20	8.60	8.30	7.70	9.80	9.50	10.30	9.70	9.40
EC (dS m ⁻¹)	3.27	1.38	1.32	3.21	2.34	1.64	1.93	0.92	0.67	1.02	1.19	1.86	3.15	1.58	1.31
Ex.Na	57.84	54.92	53.92	93.68	61.42	53.48	28.26	17.18	6.68	4.16	26.77	48.18	33.27	44.63	34.4
Ex.K	1.35	0.80	0.50	1.37	1.27	1.22	2.32	1.20	0.91	0.76	0.68	1.00	1.25	1.19	1.17
Ex.Ca	6.05	2.13	0.59	2.86	2.20	0.78	7.94	6.08	7.74	25.28	10.52	6.44	3.66	2.81	2.34
Ex.Mg	2.57	2.62	3.41	1.32	3.33	3.95	10.79	13.29	13.90	5.10	4.62	3.92	1.56	3.47	5.33
SAR (%)	27.86	35.64	38.13	64.8	36.94	34.78	9.23	5.52	2.03	1.07	9.73	21.17	20.59	25.19	17.57
ESP (%)	40.23	51.82	55.53	95.26	53.75	50.53	12.48	6.95	1.75	0.32	13.22	30.26	29.41	36.25	24.90
S-a-s- c ^a	Sodic	Sodic	Sodic	Sodic	Sodic	Sodic	Non	Non	Non	Non	Non	Non	Sodic	Sodic	Sodic
Na ⁺	565.36	481.50	445.07	947.83	547.51	496.19	318.52	160.20	166.97	72.01	249.60	509.60	715.65	383.22	432.90
K ⁺	42.65	26.27	23.58	44.72	33.51	30.11	36.43	23.73	22.87	14.47	15.10	29.65	25.64	18.00	23.12
Ca ²⁺	126.00	109.00	121.00	163.50	130.00	103.00	177.60	200.00	100.00	80.00	130.00	160.00	230.00	180.00	100.00
Mg ²⁺	189.00	109.00	121.00	43.60	80.00	154.50	122.10	120.00	230.00	250.00	170.00	90.00	120.00	180.00	175.00
Cl ⁻	302.02	276.64	272.98	184.43	279.18	159.75	156.51	276.08	205.3	179.63	259.44	290.18	141	131.98	179.63
SO ₄ ²⁻	5.10	6.87	4.31	67.60	5.40	5.05	9.87	6.53	2.84	6.77	3.87	6.53	11.39	4.31	3.82
NO ₃ ⁻	0.31	0.03	0.01	6.37	1.46	0.17	0.00	0.02	0.07	0.03	0.00	0.06	2.09	0.41	0.39
CO ₃ ²⁻	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
HCO ₃ ⁻	33.93	11.43	14.00	30.00	18.52	3.33	12.50	17.50	12.00	9.00	18.18	30.00	65.00	12.50	3.03

^aS-a-s-c: salt-affected soil class, Sodic: Sodic soil and Non: Non-saline-non-sodic soil

2.3.8 Multivariate analysis between chemical properties of the soils

2.3.8.1 Correlation between selected chemical properties

The correlations between specific soil chemical parameters were shown in Table 2.6 as Pearson correlation matrix. The soil salinity indices were also correlated with each significant correlation with soil pH, exchangeable Na, soluble Na⁺, and ESP while negatively correlated with Cl⁻, Mg²⁺, TN, ex. Mg, and ex. Ca. The ex. Na showed a significant positive correlation with pH, EC, CEC, BS, Av. P, OC, ESP, and Na⁺ while negatively correlated with ex. Ca, ex. Mg, Mg²⁺, and TN. The soil HCO₃⁻ indicated a significant positive correlation with soluble Na⁺, and K⁺. Exchangeable Ca showed negative significant correlations with Cl⁻, NO₃⁻ and HCO₃⁻.

Generally, the correlation coefficient results between the selected soil chemical properties were similar to the reported correlations between similar soil properties in literature (Choudhury et al., 2021; Guo et al., 2020; Przydatek and Kanownik, 2021). Correlation results, and a close view of other soil chemical parameters in this study, indicated that the possible major soil salt anions in Abaya and Chamo Lakes were Cl⁻ and HCO₃⁻. On the other hand, the major salt cations were Na⁺ and Mg⁺ which were relatively higher amounts than K⁺ and Ca⁺. NaCl, MgCl₂, NaHCO₃, and KHCO₃ may therefore be the principal soil salt chemical components in this region, with considerably larger quantities than CaCl₂ and CaHCO₃. These findings were supported by the findings of Daniel (2019). However, in order to completely understand salt compounds in the soils of the area and provide more targeted salinity management choices, a study on chemical salt speciation would be necessary.

Table 2. 6: Pearson Correlation between selected chemical properties

	pH	EC	Ex.Na	Ex. K	Ex.Ca	Ex.Mg	CEC	BS	Av.P	OC	TN	ESP	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	NO ₃ ⁻	HCO ₃ ⁻	
pH	1.00																			
EC	.553*	1.00																		
Ex.Na	.757**	.661**	1.00																	
Ex. K	0.15	0.31	0.12	1.00																
Ex.Ca	-.690**	-0.24	-.629*	-0.14	1.00															
Ex.Mg	-.694**	-0.50	-.684**	0.22	0.23	1.00														
CEC	0.31	.706**	.618*	0.34	-0.21	-0.40	1.00													
BS	.638*	0.44	.880**	0.05	-0.46	-.581*	0.26	1.00												
Av.P	0.47	.742**	.648**	0.48	-0.37	-0.31	.647**	0.47	1.00											
OC	0.15	.705**	0.44	.668**	0.06	-0.12	.797**	0.00	.658**	1.00										
TN	-0.30	.544*	-0.42	-0.08	0.33	0.29	-.688**	-0.07	-0.46	-0.39	1.00									
ESP	.676**	.674**	.970**	0.01	-.616*	-.681**	.670**	.791**	.614*	0.41	-.556*	1.00								
Na ⁺	.809**	.859**	.875**	0.22	-.600*	-.695**	.623*	.669**	.713**	0.48	-0.46	.860**	1.00							
K ⁺	0.50	.654**	.700**	.600*	-0.40	-0.20	0.50	.678**	.732**	.694**	-0.25	.612*	.699**	1.00						
Ca ²⁺	0.36	0.43	0.10	0.45	-0.27	0.02	0.04	0.03	0.40	0.22	-0.19	0.04	0.32	0.19	1.00					
Mg ²⁺	-.576*	.555*	-.716**	-0.26	.590*	0.32	-0.45	.615*	-.646**	-0.42	0.33	-.683**	-.699**	-.567*	-0.49	1.00				
Cl ⁻	0.13	-0.22	0.17	-0.38	-0.08	-0.02	-0.39	0.47	0.00	-0.32	0.29	0.08	-0.05	0.15	-0.20	-0.23	1.00			
NO ₃ ⁻	0.39	.937**	.643**	0.21	-0.22	-0.39	.794**	0.37	.747**	.704**	-.576*	.694**	.769**	.548*	0.30	.560*	-0.23	1.00		
HCO ₃ ⁻	0.51	.641*	0.20	0.12	-0.10	-0.36	0.02	0.16	0.43	0.16	-0.17	0.16	.551*	0.30	.671**	-0.34	0.02	0.42	1.00	

*, ** Show significant correlations at $P \leq 0.05$ and 0.01 , respectively.

2.3.8.2 Principal components analysis (PCA) of selected chemical properties

The Principal Components Analysis (PCA) biplot of selected soil chemical properties data show the loading of each variable (arrows) and the rate of each selected soil chemical properties and salinity indicating soil parameters (points). About 90% bivariate characteristics of the rate of each soil parameter are given for each site. The arrows' length indicates the variables' variance, whereas the angles between them (cosine) approximate their correlations. Close together points correspond to observations with similar rates on the PCA components. The value of that observation on the variable that the arrow signifies is generally approximated by the cut-point of a perpendicular from a point to an arrow. According to the biplot, soil salinity indicators including pH, EC, ESP, and exchangeable Na have high positive correlations with each other, while CEC, OC, ex. K, and BS have less correlations with one another and have strong negative correlations with ex. Ca and ex. Mg. In terms of depth, the majority of the research pits and sites are affected by soil salinity and sodicity, necessitating the use of calcium-rich soil amendment materials for reclamation (Figure 2.2 and Table 2.7).

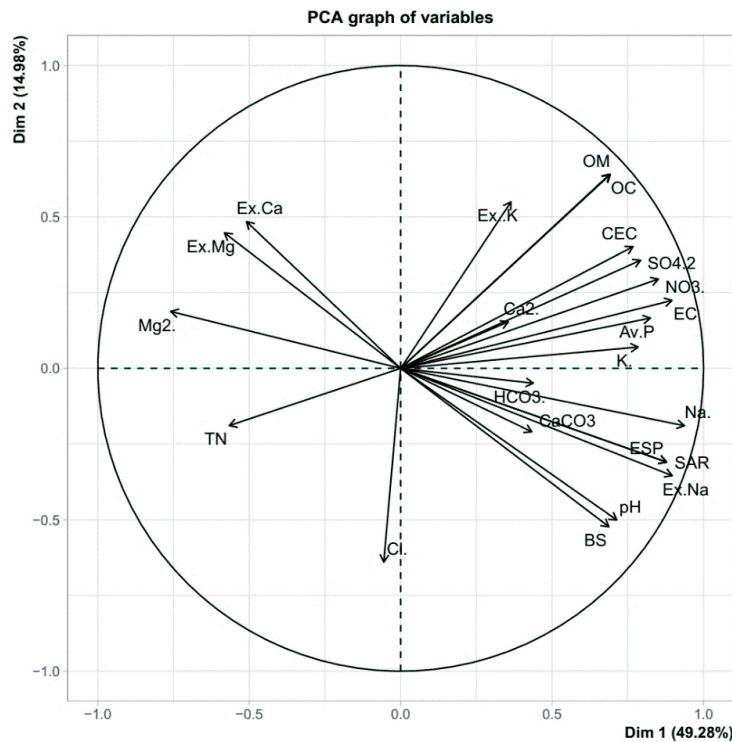


Figure 2. 2: Principal components analysis plot of soil chemical properties.

The results showed four principal components (PCs) with eigenvalues greater than 1, so they were considered, and the others were neglected. The four PCs explained 82.01% of the studied chemical soil properties' variability: 49.28%, 14.97%, 10.49%, and 7.25% for PC1, PC2, PC3, and PC4, respectively. According to factor loadings, it was clear that soil pH, EC, SAR, ESP, CEC, BS, and Av. P were correlated with PC1. On the other hand, ex. K, ex. Mg, and OC, were correlated with PC2, while PC3 was correlated with CaCO₃, and PC4 correlated with ex. Ca (Figure 2.2 and Table 2.7).

Table 2. 7: Principal components analysis of soil properties

PCA	Loading Matrix				PCA	Formatted Loading Matrix			
	Dim.1	Dim.2	Dim.3	Dim.4		Dim.1	Dim.2	Dim.3	Dim.4
Eigenvalue	11.33	3.44	2.41	1.66	Eig. V	11.33	3.44	2.41	1.66
Variance (%)	49.28	14.97	10.49	7.25	V (%)	49.28	14.97	10.49	7.25
Cumulative Variance (%)	49.28	64.26	74.75	82.01	C.V (%)	49.28	64.26	74.75	82.01
pH	0.71	-0.50	0.29	-0.14	Na ⁺	0.94	-0.19	0.04	-0.15
EC	0.90	0.22	0.07	-0.25	Ex.Na	0.90	-0.35	-0.19	0.14
Ex.Na	0.90	-0.35	-0.19	0.14	EC	0.90	0.22	0.07	-0.25
Ex. K	0.36	0.55	0.49	0.41	SAR	0.88	-0.31	-0.34	0.00
Ex.Ca	-0.51	0.48	-0.08	-0.01	ESP	0.88	-0.31	-0.34	0.00
Ex.Mg	-0.58	0.45	0.16	0.33	NO ₃ ⁻	0.85	0.29	-0.16	-0.23
CEC	0.77	0.40	-0.39	-0.06	Av.P	0.82	0.17	0.15	0.11
BS	0.69	-0.52	-0.05	0.39	SO ₄ ⁻²	0.79	0.36	-0.23	-0.07
Av.P	0.82	0.17	0.15	0.11	K ⁺	0.78	0.07	0.15	0.49
OC	0.69	0.64	-0.04	0.26	CEC	0.77	0.40	-0.39	-0.06
OM	0.69	0.64	-0.04	0.26	pH	0.71	-0.50	0.29	-0.14
TN	-0.57	-0.19	0.29	0.40	OC	0.69	0.64	-0.04	0.26
CaCO ₃	0.43	-0.21	0.67	0.08	OM	0.69	0.64	-0.04	0.26
SAR	0.88	-0.31	-0.34	0.00	BS	0.69	-0.52	-0.05	0.39
ESP	0.88	-0.31	-0.34	0.00	Ex. K	0.36	0.55	0.49	0.41
Na ⁺	0.94	-0.19	0.04	-0.15	Ex.Mg	-0.58	0.45	0.16	0.33
K ⁺	0.78	0.07	0.15	0.49	Ca ²⁺	0.36	0.15	0.76	-0.29
Ca ²⁺	0.36	0.15	0.76	-0.29	CaCO ₃	0.43	-0.21	0.67	0.08
Mg ²⁺	-0.76	0.19	-0.15	-0.13	HCO ₃ ⁻	0.44	-0.05	0.61	-0.45
Cl ⁻	-0.06	-0.64	0.05	0.45	Cl ⁻	-0.06	-0.64	0.05	0.45
SO ₄ ⁻²	0.79	0.36	-0.23	-0.07	Ex.Ca	-0.51	0.48	-0.08	-0.01
NO ₃ ⁻	0.85	0.29	-0.16	-0.23	TN	-0.57	-0.19	0.29	0.40
HCO ₃ ⁻	0.44	-0.05	0.61	-0.45	Mg ²⁺	-0.76	0.19	-0.15	-0.13

NB. The values in bold represent essential contributions above the expected value if the contributions were uniform.

2.3.8.3 Hierarchical cluster analysis of selected chemical properties of the soils

The selected soil chemical properties analysis on the five pits depth-wise around Abaya and Chamo Lakes were processed using multivariate numerical techniques using the R software. Accordingly, the agglomerative hierarchical cluster analysis was applied to this study. These are the most ubiquitous clustering algorithms. This algorithm shows the relationship between individual data and cluster relationships. The algorithm is addressed by effectively connecting small clusters following the inter-cluster distance. Eventually, a dendrogram revealed the relationship between the individual data and clusters. The height of the dendrogram refers to the distance between clusters.

The hierarchical cluster analysis on the distance from selected soil chemical properties (especially salinity indicating soil parameters) revealed three clusters. Cluster in the black color for surface soil depth (0-20 cm) of pit CL02 (around Chamo Lake) was categorized as one cluster since it has the highest value of pH (10.3), ex.Na (93.68cmol kg^{-1}) and ESP (95.26%). Cluster green color was clustered as second, including surface soil depth (0-20 cm) from the pit, AL02, and sub-surface depth (20-40 cm) from the pit, AL01 around Abaya Lake. The cluster in red color represented the third cluster, including all depths in pits CL01 and CL02 except soil depth 0-20 cm of Pit CL02 around Chamo Lake, which were categorized as sodic soils. The cluster in blue color was clustered as the fourth cluster and represented only surface depth (0-20 cm) of pit AL03. The others clustered in black color were clustered in the fifth group, including most of the Pits, around Abaya Lake: Pit, AL01 (0-20 and 20-40 cm), Pit, AL02 (20-40 cm), and Pit, AL03 (20-40 and 40-60 cm) (Figure 2.3).

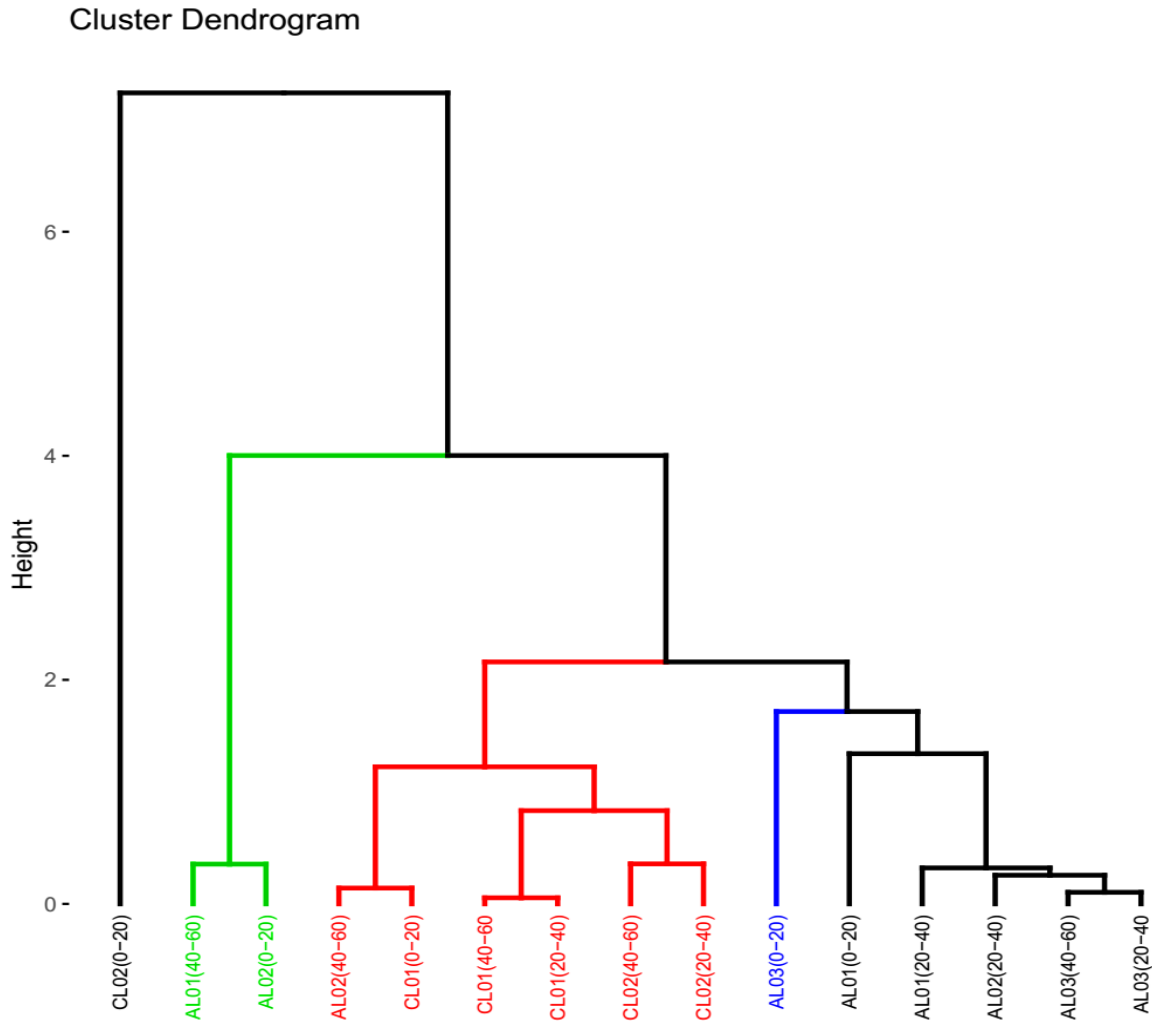


Figure 2. 3: Cluster dendrogram of chemical properties of the soils with respect to soil pits with depths (cm) wise. Where: CL01 and CL02 are pits around Chamo Lake and AL01, AL02, and AL03 are pits around Abaya Lake, respectively

Where the color in agglomerative hierarchical cluster analysis notes that assuming the soils within a cluster have similar properties, they require the same management.

2.3.8.4 K-means clustering of selected chemical properties

We also used K-means clustering for sampled pits with depth-wise study for the type of salt for the reclamation purpose of the study area. This K-means clustering is another standard algorithm method that divides or partitions the data points into a pre-determined “K” number of clusters. Based on that, K-means were clustering the study site depth-wise and grouped it into five clusters. Cluster 1, in red

color, was the pits depth 40-60 cm and depth 0-20 cm for pits AL01 and AL02, respectively, and were classified in salt-affected soil classified into non-saline non-sodic soils (FAO, 2020). Cluster 2, in orange color, was the depth-wise for pits AL01, CL02, and AL03 which were classified in salt-affected soil into non-saline non-sodic and sodic soils, respectively, according to FAO (2020). Cluster 3, in green color, was clustered for all depth levels, except for 0-20 cm depth of pit CL02 around Chamo Lake, that were classified as sodic soils (Figure 2.4).

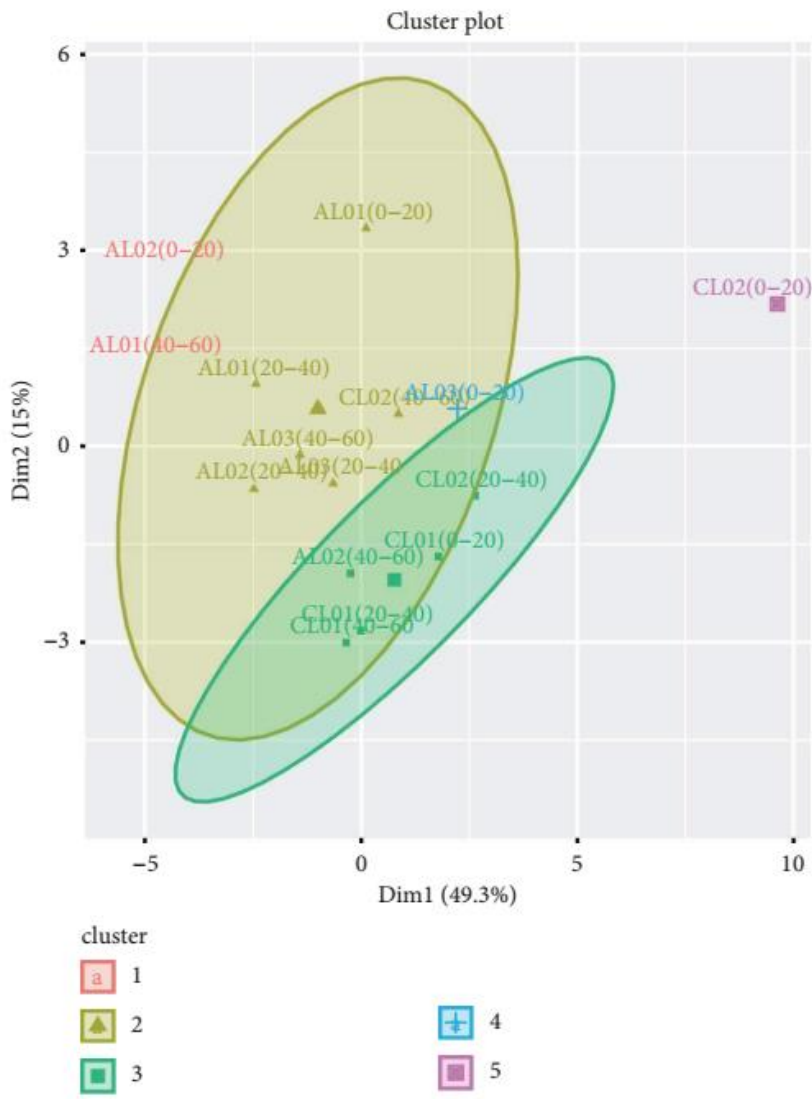


Figure 2. 4: K-means clustering of chemical properties of the soils with respect to soil pits with depths (cm) wise.

2.4 Conclusions

Soil pits were used to assess and characterize the extent, nature, and distribution of salinity and sodicity in five pits along different soil depths (0-20, 20-40, and 40-60 cm) in agricultural soils around Abaya and Chamo Lakes of southern Ethiopia Rift Valley. Soils are developed from Colluvium sedimentary and lacustrine deposits and need better drainage. A brownish to black soil color of the studied agricultural soils could be due to the dispersion of soil organic matter and humic substances. The blocky structure of soils could be due to high clay content.

Soil texture varied in the surface and subsurface layers, with silt-to-clay ratios greater than 0.3 indicating the soils are young. The soils of the study site were highly alkaline and had very high sodium content, had very high CEC value, very low level of total nitrogen, low levels of organic carbon and exchangeable calcium. Sodium was the dominant cation, followed by magnesium, calcium, and potassium in all soil depths of the pits. The soluble Na^+ content of the soils consistently decreased with increasing soil depth. This could be due to the movement of soluble and exchangeable Ca to soil depth by leaching, displacing the exchangeable and soluble sodium. Among the anions, Cl^- was dominant throughout the soil depth, followed by HCO_3^- , SO_4^{2-} , and NO_3^- . The soils of pits CL01, CL02, and AL03, except pits AL01 and AL02 (non-saline non-sodic), met the criteria to be classified as a sodic soil because the pH was greater than 8.5, EC was less than 4 dS m^{-1} , and the ESP was greater than 15%. Though soil properties revealed productivity and fertility of the soils, to the results should be assessed in detailed soil fertility studies, specifically through mapping.

The results of this study suggest that the salt content must be removed from the soil depth via drainage and leaching to increase the productivity of these soils, since this will inhibit the growth of many crops. In addition, sand mixing with clay soils is also needed to improve the soil's physical properties and drainage system. The lack of fresh water for leaching and its expense, however, could make drainage more feasible. Therefore, it would be better to use wood plants and crops that can withstand salt. Furthermore, adding organic material to the soils is advised since the soils contain low amount of organic matter. The study underscores the need for a scientific reclamation program of soils and irrigation water sources and a site-specific soil characterization to increase the production and productivity of the study area.

2.5 References

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3. NUTRIENT CONTENTS AND MAPPING OF FERTILITY STATUS OF SOILS AROUND ABAYA AND CHAMO LAKES, SOUTHERN ETHIOPIA RIFT VALLEY

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ABSTRACT

Comprehending soil's physical, chemical, and biological properties and mapping can assist in implementing appropriate agricultural technologies and effectively designing strategies for managing soil fertility. Thus, the study were conducted to analyze the nutrient contents of the soils, determine the fertility status of soils surrounding the Abaya and Chamo lakes, and map the fertility status of the soils. To obtain representative soil samples, the sampling method and sample quantity required for the study area were determined using information gathered from a reconnaissance survey and topographic map. Based on the information, 300 soil samples were collected using a systematic sampling technique from two depths (0-20 and 20-40cm), with a 600 m sampling interval, of which 100 composite soil samples were used for the study. The data were analyzed using descriptive and geostatistical approaches and standardized analytical methodologies for soil data. The results revealed that the soil textural classes in the area were mainly clay, heavy clay, and sandy clay loam. The soils were dark brown to black, with angular and sub-angular blocky structures in the surface and subsurface layers respectively. The soils were highly variable in soil properties due to their heterogeneous salt-affected nature and texture. The bulk density of the soils were extremely variable since the area was dominated by clay soil texture. The surface soil had a higher available water holding capacity (AWHC) than the subsurface counterparts, indicating more plant water storing space in the surface layers. The soils had an alkaline pH (>8.5), moderately (2-4 dS m⁻¹) to highly saline (4-8 dS m⁻¹) EC values, high exchangeable sodium percentage (50 -70%), high soil CEC (>40 cmolkg⁻¹), low OC (0.5-1.5%), very low total nitrogen content (<0.1%), high potassium availability (>300ppm), and lower calcium carbonate content. Micronutrient analysis showed high levels of iron, manganese, and copper in the soils, while zinc was low. The surface soil contained

more phosphorus than the subsurface soil. Based on the study's findings, the area was fertile; however, incorporating organic matter into the soil could enhance its structure, water retention, and nutrient availability, reducing salinity and sodicity. Moreover, additional nitrogen fertilizer would be necessary to increase crop production and yield. Besides, additional fertilizers are needed for deficient soil nutrients. Furthermore, the analytical results from the present should be verified with field trials to draw sound conclusions.

Keywords: Agricultural soils, semi-arid region, soil fertility mapping, soil properties.

3.1 Introduction

In sub-Saharan African nations, restoring soil fertility is the fundamental biophysical prerequisite for raising food production (Chikowo et al., 2014). Ethiopia's agricultural production is the foundation of the country's economy which has been heavily reliant on natural resources (Gebre and Gebremedhin, 2019). The ultimate viability of any agricultural system is determined by its soil, a dynamic natural resource which is replenished slowly (Schoonover and Crim, 2015). There are links between land use, vegetation productivity, water flow, water quality, and soil. Soils meet basic food, fuel, and fodder needs for humans and animals (Hossain et al., 2020). However, as a result of changes in soil properties brought about by the growing population's need for food, minerals have been depleted and soil productivity has been decreased (Byrnes and Bumb, 2017). This necessitates a methodical assessment of soil resources in terms of their quantity, distribution, qualities, and potential for use. This is crucial for creating a land use system that will effectively increase crop production while maintaining sustainability (Al Mamun et al., 2022).

To address the mismatch between fertilizer types and crop nutrient demand, it is imperative to understand the site-specific variability in nutrient supply of the soils when applying nutrients (Agegnehu et al., 2023). Salinity and sodicity cause a significant portion of land to become unproductive every year. Ethiopia's primary challenges are still soil salinity and sodicity in the lowlands and soil acidity in the highlands as a result of the country's reliance on rainfed agriculture (Regassa et al., 2023). Particularly in arid and semiarid areas where irrigation is practiced, soil salinization is becoming more of a problem (Pulido-Bosch et al., 2018). The environment, agricultural ecosystems, and human life are all at risk as a result of the alarming rate at which soil deterioration brought on by saltwater and sodicity is increasing (Právělie, 2021). Soils affected by salt are found

all throughout the world, and no continent is exempted from this problem (Basak et al., 2022). According to reports, salt affects around 11 million hectares of Ethiopia's soil (Borena and Hassen, 2022; Habtamu and Wassie, 2022). The dry and semiarid lowlands as well as the Rift Valley regions of Ethiopia are typically host to naturally salt-affected areas, which are distinguished by increased evapotranspiration rates relative to precipitation (Challa et al., 2022). This problem deleteriously impacts soil fertility, and reducing soil productivity (Bisht and Chauhan, 2020). Furthermore, issues arise from soil physical property changes caused by excess exchangeable Na, leading to water infiltration, air movement, root penetration, and seedling emergence problems (Choudhary and Kharche, 2018).

Determining the current georeferenced soil fertility status and irrigation water management approaches that contribute to the problem of soils is necessary to find solutions for those problems (Choukr-Allah et al., 2023). Soluble salts in irrigation water should not be present in proportions that are detrimental to hot, dry conditions in order to protect sensitive plants or the soil's natural qualities (Hailu and Mehari, 2021). According to Jayakumar et al. (2015), such quality of water is not enough to supply all the water required by the crops growing in these semi-arid and arid regions. Farmers are compelled to use all available irrigation water sources, regardless of quality, under these circumstances (Gerdes et al., 2022). This process tends to cause damage soils by salt that gradually develop. Soil management and crop production decision-making so largely depend on understanding the types and characteristics of soils as well as the quality of irrigation water (Mandal et al., 2018).

Creating a soil map necessitates knowing the basic principles of soils, including how they originate, occur globally or across landscapes, and react to various uses and management techniques (Binkley and Fisher, 2019). Thus, an understanding of the physical, chemical, and biological characteristics of soil and its mapping can aid in the application of suitable agricultural technologies and efficient design of soil fertility management strategies (Rossel and Bouma, 2016). Another goal of soil mapping is to fill in the knowledge gaps about the characteristics and processes of soil in both space and time (Fekadu et al., 2018a). Enhancing and maintaining soil fertility and productivity requires regular examination of key soil parameters and how they react to changes in land use (Abuye et al., 2021). It is also necessary to map the spatial variability of soil fertility with respect to salt-affected soil using a geographic information system (GIS) to obtain data for both current and future applications (Oshunsanya and Aliku, 2016). Determining the nutrient/fertilizer requirements for

places that are lacking the required elements, as well as tracking changes in soil fertility brought on by soil dynamics altered by salt, may all be done via soil fertility mapping (Worku et al., 2015).

The Ethiopian Soil Information System (Ethio SIS) recently created a soil fertility map for fertilizer recommendations in various regions of the nation and published soil maps in thirty districts of the nation (EthioSIS, 2016). To track the changes and reveal the soil fertility status under various soil types and soil analysis and mapping of soil fertility are required (Worku et al., 2015). The majority of the nation's limited soil maps are of smaller-scale representations and scattered across regions with little analytical data, which make them unhelpful for essential interpretations and site-specific land use decision-making (Fekadu et al., 2018b). Therefore, in order to understand soil resources and predict and map soil patterns and distribution more precisely, it is essential to do comprehensive analysis and mapping of soil (Brevik et al., 2016).

The Abaya and Chamo Lakes area in the south Ethiopian rift valley is a central agricultural region of enormous potential for crop production, particularly horticultural crop production. However, the soils in this area are highly susceptible to salt accumulation, which can significantly impact crop production and can cause several problems for crops, including reduced water infiltration and plant growth, nutrient deficiencies, and yield losses.

Management and exploitation of soil potential strictly depend on the critical and detailed study, analysis, and mapping of soils' fertility status in the designated area. In order to establish management strategies that increase crop productivity, it is imperative to map and analyze the fertility status of the soils in this region. Nonetheless, baseline data on the nutrient status of the soils in the research area's agricultural soils must be studied. Thus, the aim of the study is to map the fertility status as well as the nutrient contents of soils to successfully produce crops and implement land use planning.

3.2 Materials and Methods

3.2.1 Method of sampling and sample collection

A reconnaissance survey was carried out prior to the collection of samples to determine the degree of soil variability or homogeneity based on differences in physiography, land use, and visually detectable soil properties (soil texture, drainage condition, and salt crust at the soil surface,). Following these, the sampling technique and sample size required to adequately represent the study

area were decided. The topographic map of the research area (scale 1:50,000) and reconnaissance survey data were used to identify sampling places and points, which were then categorized into five map units. Three representative soil sampling regions were chosen and collected from each map unit and homogenized to prepare composite soil samples. For this investigation, 300 auger soil samples were collected, and 10 auger soil samples were used to make one composite soil sample with a 600 m sampling interval. Rearranging the sampling depth will lead to surface (0–20 cm) and sub-surface (>20 cm) samples for saline or saline-alkali soils (Wogi et al., 2021). Accordingly, 100 soil samples that were collected using a systematic sampling technique from two depths (0-20 cm and 20-40 cm) were used to assess soil fertility status and mapping since the study area is salt-affected. The soil fertility status in the research area was mapped using the analytical results of the surface soil samples.. Every sampling point was georeferenced, and the dates of taking the samples were accurately recorded.

3.2.1.1 Soil sample preparation

The soil samples were air dried, ground to pass through a 2 mm sieve, and then the physicochemical properties of the soils and their fertility indicators were determined. Soil laboratory analyses were performed at Arba Minch University, the Engineering Corporation of Oromia, and at the Ethiopian Design and Water Works in Addis Abeba, Ethiopia.

3.2.1.2 Analysis of soil physical and chemical properties

The texture of the soil, bulk density (BD), particle density (PD), total porosity, soil pH, Electrical conductivity (EC), organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), exchangeable bases, available phosphorus (Av. P), the moisture contents at field capacity (FC), permanent wilting point (PWP), the available water content (AWC) and micronutrient (Fe, Mn, Zn, and Cu) contents of the soils were done as presented under section 1.4. Derived parameters: using equations 1 and 2, PBS and ESP have been calculated as the percentages of the total of exchangeable bases and exchangeable Na to the soil's CEC, respectively.

$$PBS(\%) = \frac{\sum \text{Exchangeable base } (Ca^{2+} + Mg^{2+} + K^+ + Na^{2+})}{CEC} * 100 \dots \dots \dots (1)$$

$$ESP(\%) = \sum \text{Exchangeable base } (Na^{2+}) / CEC * 100 \dots \dots \dots (2)$$

3.2.2 Geostatistical analysis and mapping of selected soil fertility parameters

When samples were taken, GPS pinpointed their exact locations. Next, the salinity and sodicity parameters of the soil were analyzed. To create maps of the soils in the area, salinity and sodicity characteristics were interpolated using a geostatistical analyst extension tool in QGIS software. Following that, the research area was defined and divided into mapping units. The whole area of the study location as well as the Easting and Northing coordinates of each map unit were carefully recorded.

The combination and final computation of intermediate surfaces based on the combination decision rule and basic questions were performed using the Raster Algebra analysis capabilities of the Spatial Analyst extension. Based on the findings and ratings of soil laboratory analyses, the area of each map unit was also rated (very low, low, medium, high, and very high). Lastly, a map of the soil fertility status of the research area was created. The accuracy of the interpolation techniques was evaluated via cross-validation using mean error (ME), root mean square standardized error (RMSSE), and root means square error (RMSE) (Arétouyap et al., 2016). Selecting the best-fitted semivariogram model for an interpolation map was made easier by values of the mean error (ME) and root mean square standardized error (RMSSE) being closer to 0 and 1, respectively, indicating that the prediction values were close to the measured values (Ferreira et al., 2015).

Ordinary kriging was employed to interpolate values for unsampled locations and create maps of soil properties (Robinson and Metternicht, 2006). Due to its excellent performance, ordinary kriging is the most widely used method for generating maps that depict the spatial variability of soil (Dai et al., 2014; P. Kumar et al., 2023). The spatial variation was quantified using an input dataset of point data, and a semivariogram was generated from the scatter point set that required interpolation. Semivariograms were calculated to analyze the structure of spatial variability, as demonstrated by the equations provided below (Costa et al., 2015; Oueslati et al., 2013)

$$y(h) = \frac{1}{2n} \sum_{n=1}^n Z(Xi) - Z(Xi + h)^2 \quad (3)$$

Where: n is the number of pairs of sample points separated by the distance h, and Z (xi)'s are the value of the characteristic under study at the ith location (i = 1, 2, 3 . . . n).

$$\text{RMSSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\{Z(Xi) - \check{Z}(Xi)\} / \sigma(Xi))^2} \quad (4)$$

$$\text{MSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n \sigma^2(X_i)} \quad (5)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (Z(X_i) - \check{Z}(X_i))^2} \quad (6)$$

Where n is the sample size, $\sigma^2(X_i)$ is the kriging variance for location X_i , $v(X_i)$ is the predicted value at location I , and $Z(X_i)$ is the value of the variable Z at location X_i .

The performance or effectiveness of interpolation was assessed using the Goodness of Prediction Estimate (G) (see eq. 7) (Fanuel et al., 2018; J. Li and Heap, 2011; Robinson and Metternicht, 2006). A "G" value of 100% signifies a perfect prediction, while positive values ranging from 0% to 100% suggest that the predictions are more reliable than using the sample mean. In contrast, negative values indicate that the predictions are less reliable than the sample mean.

$$G = 1 - \frac{\sum_{i=1}^n (Z(X_i) - \check{Z}(X_i))^2}{\sum_{i=1}^n (Z(X_i) - \hat{Y})^2} \times 100 \quad (7)$$

Where: $Z(x_i)$ is the observed value at location i , $\check{Z}(x_i)$ is the predicted value at location i , n is the sample size, and \hat{Y} is the sample mean.

Three important parameters—nugget (C_0), sill ($C_0 + \text{partial sill } (C)$), and range—were derived from the fitted models to identify the spatial structure of the measured variables (Irvine et al., 2007). The nugget represents the variance at zero distance and includes unavoidable sampling or experimental errors that may occur during analysis (Denton et al., 2017; Gramacy and Lee, 2012). The sill ($C_0 + C$) indicates the lag distance at which one measurement of a variable does not influence neighboring measurements, effectively representing the total variation. The ratio of the nugget to the sill is used as a criterion for classifying spatial dependence (Abdu et al., 2023; Fanuel et al., 2018). The range indicates the distance beyond which values of one variable become spatially independent of another. Essentially, it reflects the distance at which the variation (as indicated by the sill) stabilizes to a constant value. If the sampling interval between two locations for a particular variable is shorter than the range distance, the variable is considered spatially auto-correlated (Abdu et al., 2023; Costa et al., 2015). During the map preparation process, first created maps that indicated areas with sufficient and deficient nutrients for each parameter, based on predetermined ratings (Abdu et al., 2023; Denton et

al., 2017). Afterward, we used spatial analysis tools to overlay these individual parameter maps that highlighted the nutrient-deficient areas. This approach enabled us to produce a comprehensive nutrient-type map for site-specific management.

3.2.3 Data analysis

Descriptive statistics data were analyzed using SAS software, version 9.4 (Blanca Mena et al., 2017). The rating of determined values was based on a guide to standardized analytical methodologies for soil data (Wogi et al., 2021). Nutrient variability was determined using the coefficient of variation. The variability is low when the CV is $< 10\%$, moderate between 10 and 100%, and strong when $> 100\%$ (Terefe et al., 2021). The laboratory analytical results were imported into a GIS environment to determine the geographical distribution of soil fertility status in the investigated area. The data were entered into Microsoft Excel with their corresponding coordinates (Latitude and Longitude). Spatial prediction and mapping of the un-sampled surface from laboratory point data were done in a GIS environment using interpolation techniques. From laboratory point data, the un-sampled surface was predicted and mapped using the standard kriging method in QGIS software (Takele and Iticha, 2020).

3.3 Results and Discussion

3.3.1 Geostatistical analysis and mapping of selected soil fertility parameters

Table 3.1 displays the findings of the soil spatial analysis. The ratio of nuggets to sill or spatial dependence $C_0/(C_0 + C)$ is the spatial property definition. When the value of $C_0/(C_0 + C)$ is less than 0.25, the variable is said to have a strong spatial dependency; when it is between 0.25 and 0.75, it is considered to have a moderate geographic dependence; and when it exceeds 0.75, it is considered to have a weak spatial dependence (Addis et al., 2015; Cambardella et al., 1994; Sani et al., 2023). The semivariogram produced by the geostatistical analysis is displayed in Table 3.1 and provides various models of the soil characteristics' spatial distribution and degrees of spatial dependency. Semivariance demonstrated that the spatial dependence of soil parameters was the same (Cambardella et al., 1994; López-Granados et al., 2002) (Table 3.1). According to Cambardella et al. (1994), for all soil investigated characteristics, a considerable geographical dependence was seen in the nugget/sill ratio $(C_0/C_0 + C) < 25\%$.

The model explained the distribution's results by demonstrating how natural factors, mostly of a geological nature, affect the data. This may be primarily caused by intrinsic or inherent causes of

variability (e.g., terrain, parent materials, and variations in soil texture) (Addise et al., 2022; Stritih, 2021). Similarly, Saleh (2018) and Corwin and Yemoto (2020) also reported that strong spatial dependence of soil properties is associated with intrinsic structural factors like parent material, texture, climate, and topography; weak spatial dependency is associated with extrinsic factors that are random, like soil management practices like fertilization and plowing (Gülser et al., 2016). Conversely, a moderate degree of spatial dependence is probably influenced by both extrinsic and intrinsic factors (Swafu and Dlamini, 2023). For soil ex. Mg^{2+} , SAR, BS, and Fe, the nugget effect was commonly high (Table 3.1). This suggested that regional heterogeneity in soil qualities existed at short distances. The spatial variability at smaller distances than the minimum separation between measurements is associated with the nugget effect (Yao et al., 2020).

The Spherical model was the highest accuracy among the other experimental semivariogram models for estimating most of the studied soil parameters. Exponential model was best fitted for the variations of soil ex. Ca and EC; while ex. K was better described by the Gaussian model for the agricultural soils around Abaya and Chamo Lakes, South Ethiopian Rift Valley. The results showed that the mean errors (ME) were nearly zero, and the root mean square standardized error (RMSSE) was approximately 1 for all examined soil parameters (see Table 3.1). This finding aligns with the work of Abdu et al. (2023), who also reported mean error values close to 0 and root mean square standardized error values near 1. This similarity suggests that the predicted values were very close to the measured values, indicating a high level of accuracy in the predictions.

The spatial range values for all investigated soil properties ranged from 3,332 m to 22,416 m, as shown in Table 3.1. Since this range is larger than the average sampling distance of 600 m, the sampling interval used in this study was adequate to capture the spatial variability in the investigated soil properties (Aishah et al., 2010; Fanuel et al., 2018).

Table 3. 1: Semivariogram models and model parameters for selected soil properties

Soil Property	Fitted Model	Nugget (Co)	Partial Sill (C)	Sill (Co + C)	Range (m)	SPD (Co/Co+C)*100	SPD Level	Estimated Error		
								ME	RMSSE	
pH	Sph	0.00	1.03	1.03	20830	0.10	Strong	-0.02	0.26	
Ec	Exp	0.00	1.16	1.16	3332	0.10	Strong	0.00	0.14	
Ex. Bases	Ca ²⁺	Exp	0.00	1.03	1.03	20984	0.10	Strong	0.03	0.34
	Mg ²⁺	Sph	0.01	1.00	1.01	22292	0.99	Strong	0.02	0.33
	Na ⁺	Sph	0.00	1.08	1.09	10263	0.17	Strong	0.01	0.15
	K ⁺	Gau	0.00	1.17	1.17	3614	0.10	Strong	0.01	0.14
	SAR	Sph	0.01	1.04	1.05	22416	0.96	Strong	-0.02	0.29
ESP	Sph	0.00	1.04	1.04	8962	0.10	Strong	0.00	0.16	
BS	Sph	0.01	1.08	1.09	8176	0.91	Strong	0.00	0.13	
CEC	Sph	0.00	1.10	1.11	5356	0.10	Strong	0.00	0.14	
Av. P	Sph	0.00	1.06	1.06	8229	0.09	Strong	0.00	0.10	
Av.K	Sph	0.00	1.13	1.13	3551	0.09	Strong	-0.01	0.14	
OC	Sph	0.00	1.10	1.11	10874	0.10	Strong	-0.02	0.13	
OM	Sph	0.00	1.11	1.11	4699	0.11	Strong	-0.01	0.14	
TN	Sph	0.00	1.12	1.13	4585	0.11	Strong	0.00	0.14	
Fe	Sph	0.01	1.11	1.12	5594	0.99	Strong	0.02	0.15	
Mn	Sph	0.00	1.10	1.10	5137	0.09	Strong	0.02	0.15	
Cu	Sph	0.00	1.07	1.07	20924	0.09	Strong	0.01	0.07	
Zn	Sph	0.00	1.13	1.13	4615	0.11	Strong	0.01	0.15	

Where: Sph = Spherical, Gau = Gaussian, Exp = Exponential

3.3.2 Soil texture

The soil texture affects organic matter concentration, cation exchange capacity, pH buffering capacity, drainage, water retention capacity, aeration, susceptibility to erosion, and soil tilth (Usharani et al., 2019). This depicts clay, heavy clay, and sandy clay loam soil textural classes, with clay texture distribution dominating (Figure 3.4). Clay soils are high in nutrients and have a high water retention capacity, making them ideal for growing a variety of crops. They can, however, be difficult to work with because they become sticky and heavy when wet (Dwevedi et al., 2017; Osman and Osman, 2013). Sandy clay loam soils are a mixture of sand, clay, and silt that have some advantages over clay and sandy soils. However, they can be prone to compaction and erosion, so tillage and water management practices are essential (Huang and Hartemink, 2020; Osman and Osman, 2018).

Surface and subsurface soil textures differ in particle size distributions, with silt-to-clay ratios greater than 0.2 indicating that the soils are young. If the silt-to-clay ratio is greater than 0.2, the soil is young

(Hundessa, 2020; Sharma et al., 2020). This is due to the fact that young soils are still in the process of pedogenesis, or soil formation (Sokolov et al., 2021). Organic matter is added to the soil during pedogenesis, which aids in the breakdown of clay particles into smaller particles. As a result, the silt-to-clay ratio increases (Fonseca et al., 2021; Mwendwa et al., 2020). The CV of soil texture had moderate variability based on ratings of Terefe et al. (2021) since its range falls CV between 10% and 100% for the studied soils.

Table 3. 2: Particle size distribution of agricultural soils around Abaya and Chamo Lakes

Depth(cm)	Descriptive Statistics	Soil separates		
		Sand, %	Silt, %	Clay, %
0-20	Mean	32.80	18.40	48.80
	SD	20.77	11.70	11.80
	Minimum	6.00	6.00	32.00
	Maximum	62.00	30.00	64.00
	CV %	63.31	63.57	24.18
20-40	Mean	28.80	24.00	47.20
	SD	20.62	12.88	14.81
	Minimum	2.00	8.00	26.00
	Maximum	50.00	34.00	66.00
	CV %	71.60	53.68	31.37

3.3.3 Soil color and structure

The most noticeable characteristic of soil that indicates the nature of the root zone is its color, which typically reflects a greater organic matter content, giving it a black or dark appearance (Khadka et al., 2019). The soils around Abaya and Chamo Lakes in South Ethiopian Rift Valley are dark brown to black in color. The color of surface soils (0-20 cm) typically ranged from very dark grayish brown (10YR 3/2) to brown (7.5YR 4/3), whereas the color of subsurface soils (20-40 cm) ranged from black (10YR 2/1) to very dark brown (7.5YR 2.5/2). This color variation is most likely caused by differences in organic matter and iron levels in the soils. Surface soils are usually higher in organic matter, giving them a darker color. Subsurface soils are typically lower in organic matter, but they may contain more iron, giving them a redder appearance (Pribyl, 2010; Senesi and Loffredo, 2018). The soils in this region are also relatively young, requiring more time to weather. This can cause an accumulation of organic matter in surface soils, giving them a darker color. The color of the soil in this region has a significant impact on the plant life that can grow there (Bouma et al., 2017). Plants

that prefer darker, more organic soils will be found in surface soils, while plants that prefer lighter, more mineral soils will be found in subsurface soils (Schoonover and Crim, 2015).

The soil structure is angular blocky at the surface (0-20 cm) and sub-angular blocky at the subsurface (20-40 cm). This means the surface layer soil particles are arranged in angular blocks, whereas the subsurface layer soil particles are arranged in sub-angular blocks. The angular blocky structure at the surface and the sub-angular blocky structure at the subsurface indicate soil compaction. The sodic characteristics of the surface soil and low organic matter content likely exacerbate this compaction (Suresh, 2017). Overall, the soil structure in agriculturally soils around Abaya and Chamo Lakes is most likely the result of a combination of factors, including the amount of clay, organic matter, and salt in the soils. This soil structure has the potential to significantly impact the region's agricultural productivity (Bedadi et al., 2023; Setegn et al., 2022; Walche et al., 2023)

3.3.4 Bulk density, particle density and porosity

One fundamental dynamic soil attribute affected by numerous physical and chemical characteristics is soil bulk density (Wubie and Assen, 2020). The ideal bulk density for plant growth in clay soils with restricted root penetration is 1.4 g cm^{-3} (Massawe et al., 2017). The higher bulk density in surface soil is likely due to more salts, which can cause soil particles to disperse and pack together more tightly. However, in contrast to these findings, lower bulk density is expected in subsurface soil due to more organic matter, which helps bind soil particles together and create larger pores (Pepper and Brusseau, 2019; Skopp, 2012). The range of bulk density values in both the surface and subsurface soils indicates that the soils in this area are heterogeneous, with more compact soils in some areas than in others. This could be due to factors such as soil type, amount of irrigation, and water table depth (Delbari et al., 2019).

The mean bulk density values of 1.40 g cm^{-3} and 1.34 g cm^{-3} are moderate, indicating that these soils are relatively compact and tight enough. However, the higher bulk density in the surface soil may limit plant rooting depth and access to water and nutrients (Singh et al., 2015). Moreover, as indicated in Wogi et al. (2021) soil rating and interpretation guideline, Landon (2014) and Jones (2001) of the critical value of bulk density in clay soils limits root penetration when it exceeds 1.4 g/cm^3 . The findings revealed that the soil in the studied area showed low variability in soil bulk density among the sampled sites for the surface soil but moderate variability for the subsurface (20-40cm) due to the

CV ranging between 10% and 100%. Generally, the bulk density of the studied soil is extremely variable since the area is dominated by clay soil texture, which is similar to the report of Wogi et al. (2021). Overall, the particle density of the agricultural soils surrounding Abaya and Chamo Lakes is moderate, but there is some variation between the surface and subsurface soils. This may have an impact on plant growth and crop yields in the area (Table 3.3). The higher porosity in the surface soil is likely due to the presence of more organic matter, which helps to bind the soil particles together and create larger pores. The lower porosity in the subsurface soil is likely due to the accumulation of salts, which can cause the soil particles to disperse and clog the pores (Guo et al., 2020). The range of porosity values in both the surface and subsurface soil suggests that the soils in this area are heterogeneous, with some areas having more porous soils than others. The coefficient of variation (CV%) indicated moderate variability among the sampled sites were moderate variability among the sampled sites. This could be due to factors such as the type of soil, the amount of irrigation, and the depth of the water table (X. Li et al., 2017).

3.3.5 Available water holding capacity (AWHC)

The available water holding capacity (AWHC) of surface soil at 0-20 cm depth is higher than that of subsurface soil (20-40 cm depth). The mean AWHC for surface soil is 18.1%, while the average AWHC for subsurface soil is 12.7% (Table 3.3). This means that more water is available for plants' use in the surface soil than in the subsurface soil layer. The AWHC for surface soil is wider compared to subsurface soil. It ranged from 14.3% to 21.5%, while the value only ranged from 7.51% to 18.04% in the subsurface layer. Interestingly, AWHC has shown less variability in the surface layer among the sampling sites, indicating that the availability of water to plants in surface soil varies more than in subsurface soil (Zhao et al., 2022). This suggests that there will be more space for water to collect on the surface soil. The better water-holding capacity of the soils in the studied area is often beneficially affected by the high distribution/content of clay fraction (Nachtergaele et al., 2023) and due to some amount of organic matter (Libohova et al., 2018).

Table 3. 3: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

Depth (cm)	Des. S	BD (g cm ⁻³)	PD (g cm ⁻³)	Porosity (%)	FC (%)	PWP(%)	AWHC(%)
0-20	Mean	1.4	2.76	49.3	50.28	32.22	18.06
	SD	0.13	0.41	8.91	4.72	3.07	3.16
	Min	1.2	2.4	39	44.21	28.94	14.34
	Max	1.52	3.3	61	57.07	36.47	21.48
	CV	9.63	14.85	18.4	9.39	9.52	9.52
20-40	Mean	1.34	2.62	48.9	49.72	37.07	12.66
	SD	0.15	0.63	11.82	6.58	3.84	3.83
	Min	1.18	1.7	27	44.82	32.99	7.51
	Max	1.55	3.3	59	61.19	43.15	18.04
	CV	11.02	23.9	26.63	13.23	10.35	10.35

3.3.6 Soil reaction (pH)

The agricultural soils around Abaya and Chamo Lakes have a very alkaline pH (Table 3.4 and Figure 3.1). This high pH is most likely due to the sodium bicarbonate (NaHCO₃ or HCO₃⁻) content of the soil.(Walche et al., 2023). High pH levels can have several negative effects on plant growth. It can makes nutrient uptake difficult for plants and makes the soil more prone to compaction. Furthermore, high pH levels can be harmful to some plant species (Chen et al., 2021; Neina, 2019; Wang et al., 2019). This study revealed an increase in alkalinity in the study area compared to the previous findings of EthioSIS (2016), which showed neutral to moderate. Hence, fast salinity and sodicity management strategies are needed in the study area. The study noticed that the pH levels have exhibited a moderate (between 10 and 100 CV%) degree of variability across the different sampling sites in the surface soil layer (0-20cm), whereas in the sub-surface soil layer (20-40cm), the variability has been relatively low(<10 CV%). There are several methods for managing high pH in soils. One of these is to amend the soil with organic matter. Organic matter can help buffer the pH and make it more plant-friendly (Gu et al., 2023). Another method for controlling pH is to use gypsum. Gypsum is useful in pH reduction and soil structure improvement (Watts and Dick, 2014).

3.3.7 Soil electrical conductivity (EC)

The EC values for the surface and subsurface soil ranged from moderately to highly saline. Surface soils had a mean EC value of 4.01 dS m⁻¹, while subsurface soil hasd a mean EC value of 3.10 dS m⁻¹. This implies that the surface soil is slightly saltier than the subsurface soil (Table 3.4). This suggests

that the surface soil has a wider range of EC value than the subsurface soil. The coefficient of variation (CV%) for EC showed moderate variability, as it ranged between 10 and 100%. The higher EC values in the surface soil as compared to subsurface soil could most likely be due to its greater exposure to the accumulation of salts. Rainfall and irrigation water, which can contain salts, could also more likely affect the salt accumulation in the surface layer (Abdennour et al., 2021; Ortiz and Jin, 2021). The findings of this study showed some of the study areas have salt accumulation in the soils around Abaya and Cham Lakes. In contrast, the studies conducted by EthioSIS (2016), indicate the soils around the study area were salt-free. This could be the soil sampling distance coverage, the area exposure to salinity and sodicity, and the time difference between the study conducted and the previous studies (EthioSIS, 2016).

3.3.8 Exchangeable bases

Most exchangeable calcium values were low, with a few being medium and very high in the soils of the study area (Table 3.4). The coefficient of variation (CV%) for exchangeable calcium showed moderate variability, as it ranged between 10 and 100%. According to Wogi et al. (2021), the study area has a low exchangeable calcium rating (Figure 3.1). This indicates that the soils in this area may require application of additional calcium for optimal plant growth. Calcium is an essential nutrient for plants, and it helps regulate other nutrients, such as potassium and magnesium uptakes (Bhatla et al., 2018; Kirkby, 2023). It also helps in the improvement of soil structure and drainage (Talukolae et al., 2018). The low exchangeable calcium content in the study area could be attributed to various factors, including the parent material, climate, and vegetation type (Alnaimy et al., 2023; Augusto et al., 2017). However, the findings of this study were in contrast to those of the previous research in the location (EthioSIS, 2016), which showed a high amount of calcium saturation and suggested detailed site-specific studies.

Potassium is one of three major essential nutrients for plants, along with nitrogen and phosphorus (Reimer et al., 2020). The majority of the exchangeable potassium values were high to very high. The very high rated exchangeable potassium distribution (Wogi et al., 2021) was dominant in the study area (Table 3.4 and Figure 3.1). The result was similar to the finding of EthioSIS (2016), which rated K as optimum to high. The coefficient of variation (CV%) for exchangeable potassium showed moderate variability, as it ranged between 10 and 100%. The presence of various minerals, optimal organic matter status, and comparative low content of sand, among other factors, might be responsible

for the satisfactory potassium conditions in the soils of the study area (Sanjivkumar et al., 2022). This indicates that the soils in this area are rich in potassium, an important nutrient for plants. Potassium plays a role in regulating plant growth, photosynthesis, and water efficiency. It also helps enhance soil structure by displacing sodium ions from the soil exchange sites and lowering the SAR (Hafez et al., 2021; Rawat et al., 2016). Monitoring potassium levels in crops and adjusting fertilizer applications to the recommended fertilizer rate is needed to avoid potassium toxicity (Yahaya et al., 2023; Zörb et al., 2014).

In living plant cells, magnesium is the second most abundant cation and is involved in several metabolic activities (Chaudhry et al., 2021). The medium rated exchangeable magnesium (Wogi et al., 2021) was dominant in the soils of study area (Figure 3.1).

The results were consistent with those of EthioSIS (2016), which determined an optimum magnesium level. This suggests that the soils in this area have sufficient magnesium for most plants. Magnesium is an essential nutrient for plants, as it regulates the uptake of other nutrients such as calcium and potassium. It also helps improve photosynthesis and chlorophyll production (Ahmed et al., 2020; Pandey, 2018). The coefficient of variation (CV%) for exchangeable magnesium showed moderate variability, as it ranged between 10 and 100%. Generally, the medium exchangeable magnesium levels in the soils of the study area indicate crop production. However, monitoring magnesium levels in crops and adjusting fertilizer applications as needed is critical to avoid magnesium deficiency (Bindraban et al., 2015; Huber and Jones, 2013). Cation imbalance occurs when the soil's relative proportions of essential cations (calcium, magnesium, and potassium) are significantly skewed. This can lead to deficiencies or excesses of specific nutrients, impacting plant growth and health (Antonangelo et al., 2024). At Ca: Mg ratio less than 5, Ca deficiency will occur, whereas if the ratio is greater than 5, Mg deficiency occurs. The Ca: Mg ratio of 2.2 suggests a relatively high magnesium concentration compared to calcium because low Ca: Mg can cause Ca deficiency (Fouhy et al., 2023). The results of Ca : Mg were similar to those of previous studies (EthioSIS, 2016). While a certain amount of magnesium is necessary for plant health, an excess can interfere with calcium uptake. This is because magnesium competes with calcium for absorption sites in the plant roots (Huber and Jones, 2013) . As a result, calcium deficiency can occur, even if there's sufficient calcium in the soil. The Mg: K ratio 3.1 indicates a higher magnesium concentration than potassium (Han et al., 2019). This imbalance can also contribute to potassium deficiency. When

magnesium levels are high, it can inhibit potassium uptake, leading to symptoms of potassium deficiency in the plant (Hafsi et al., 2014).

The exchangeable sodium values of the soils were very high (Wogi et al., 2021), and sodium was the dominant cation in the soils of the study area (Table 3.4). The coefficient of variation (CV%) for exchangeable sodium showed moderate variability, as it ranged between 10 and 100%. The soils in this area are highly saline and sodic, which could be used for crop production if properly reclaimed (Walche et al., 2023). Sodium is a highly mobile ion in the soil that can displace other cations, such as calcium and magnesium, from the exchange complex. Because, sodium ions have a higher hydration energy than calcium and magnesium ions. This means that sodium ions attract more water molecules, making them more mobile and easier to displace other cations (Chaplin, 2019; Marcus, 2009). In addition, sodium ions have a smaller ionic radius than calcium and magnesium ions. This makes them also more mobile and able to penetrate the soil pores more easily (Delgado and Gómez, 2024; Marchuk, 2013; Rengasamy and Olsson, 1991). This can result in various problems, such as poor soil structure, waterlogging, and nutrient deficiencies. The high exchangeable sodium in the soils of the study area could be attributed to many factors, including the parent material, climate, and irrigation water quality (George et al., 2012; Rezapour et al., 2017). The high exchangeable sodium levels in the soils of the study area may negatively impact crop production. Crops sensitive to salinity and sodicity, such as tomatoes and potatoes, may not thrive in this environment (Zörb et al., 2019). However, various management practices, such as gypsum application and leaching and selection of crops tolerant to salt, can be used to improve the growth of plants on the soil (Mohamed, 2017; Mohammad et al., 2018).

3.3.9 Exchangeable sodium percentage (ESP)

The exchangeable sodium percentage in the soils of the study area is very high. The mean exchangeable sodium percentage in the surface soil was 94.20%, while it was 99.12 in the subsurface soil (Table 3.4). This indicates sodium accounts for more than 94% of the exchangeable cations in the surface soil and more than 99% in the subsurface soil. According to FAO (2020), sodic soils have an exchangeable sodium percentage of 60% or higher. The soils in the study area have an exchangeable sodium percentage ranging from 94% to 99%, significantly higher than the sodic threshold. This shows that the soils in the area are highly sodic, which can have a number of negative consequences on crop production (Choudhary and Kharche, 2018; Rasouli et al., 2013). Poor soil

structure, waterlogging, and nutrient deficiencies are some of the adverse effects of sodic soils. However, several management practices can improve sodic soils, such as leaching, gypsum application, and crop selection for salt tolerance (Daba and Qureshi, 2021; Gangwar et al., 2020). The coefficient of variation (CV%) for exchangeable sodium percentage showed moderate variability, as it ranged between 10 and 100%.

3.3.10 Available phosphorus

Phosphorus deficiencies decrease crop yields as it is the second most limiting nutrient after nitrogen (Abay et al., 2022). The distribution of available phosphorus in the soils of the studied area was rated as high and very high (Figure 3.1). The available phosphorus concentration in the surface soil contains more available phosphorus than the subsurface soil (Table 3.4). This disparity could be explained by a number of factors. The surface soil may be more vulnerable to weathering and decomposition, which can lead to the release of phosphorus from organic matter. There is also a chance that the surface soil has more P containing minerals because it was freshly deposited. The top layer of soil was recently deposited and has a higher amount of phosphorus from its parent material (Alemayehu, 2018; Dill, 2016; Vitousek et al., 2010). Furthermore, soil alkaline phosphatase activity may help to explain how soil alkaline phosphatase activity raises the proportion of active and medium-active inorganic phosphorus in the soil phosphorus pool (Jiabao et al., 2021; Xie et al., 2022).

It is possible that plant consumption or leaching caused phosphorus to be depleted in the subsurface soil. A greater amount of available phosphorus in the surface soil is crucial for crop production because it is an essential mineral for plant growth (Grenon et al., 2021; Zhu et al., 2018). Farmers in the study area consider applying phosphorus fertilizer to the surface soil to increase crop yields. This study's findings revealed contrasting results when comparing the previous research of EthioSIS (2016), which showed a low available phosphorous amount. However, it is important to note that phosphorus fertilizer (like Triple Superphosphate (TSP)) can contribute to soil salinity, so it should be used with caution and in consultation with a soil scientist or agricultural expert (Hazelton and Murphy, 2016; Tóth et al., 2014). The coefficient of variation (CV%) for available phosphorous showed moderate variability, as it ranged between 10 and 100% for both surface and sub-surface soils.

Table 3. 4: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

Depth (cm)	Des. S	pH	EC (dS m ⁻¹)	Ex.Ca	Ex. K	Ex.Mg	Ex.Na	ESP (%)	Av.P (mg kg ⁻¹)
				(cmolckg ⁻¹)					
0 - 20	Mean	9.44	4.01	9.60	1.44	4.45	46.75	94.20	38.59
	SD	1.04	1.76	7.36	0.47	2.73	22.53	46.32	38.05
	Minimum	8.10	1.55	3.19	1.16	1.65	9.82	19.92	4.23
	Maximum	10.60	6.01	21.60	2.26	8.33	63.90	138.91	83.87
	CV%	10.97	43.99	76.72	32.41	61.34	48.19	49.17	98.60
20 - 40	Mean	9.44	3.10	6.92	1.14	4.79	46.96	99.12	21.44
	SD	0.78	1.50	4.78	0.13	2.38	22.66	48.59	17.08
	Minimum	8.50	1.73	2.09	0.97	2.22	16.08	35.19	12.04
	Maximum	10.40	5.10	13.98	1.30	7.92	68.22	150.93	51.83
	CV%	8.29	48.39	69.04	11.85	49.71	48.26	49.02	79.68

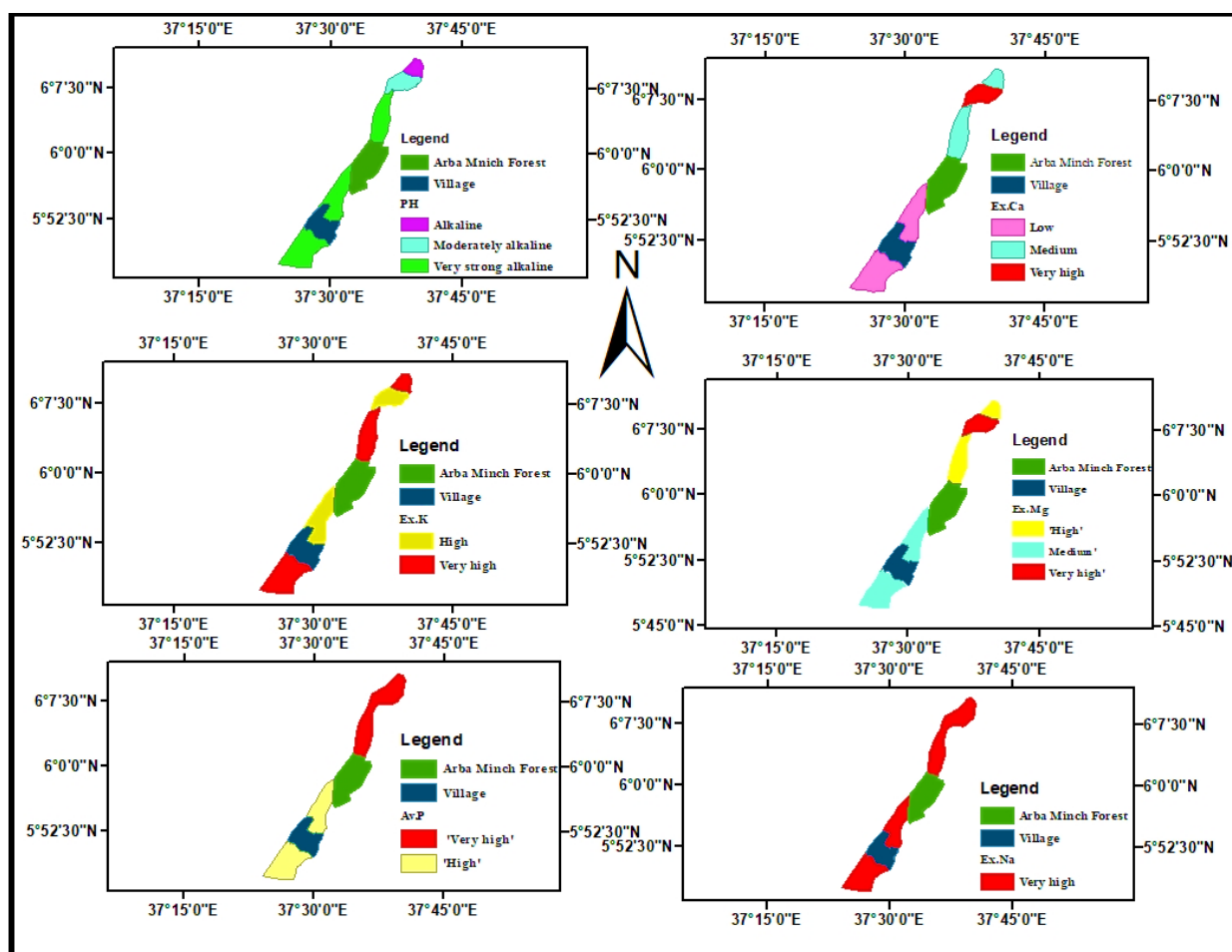


Figure 3. 1: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

3.3.11 Cation exchange capacity (CEC)

The cation exchange capacity (CEC) of the study soil was very high. These show that the soils can store nutrients (Figure 3.2). The high clay and organic matter contents of the soils and are probably responsible for this high CEC. Positively charged cations such as calcium, magnesium, potassium, and sodium can be attracted to and retained by negatively charged soil clay particles. This finding is supported by different reports (Alloway, 2012; Cross et al., 2016).

Additionally, having a negative charge, organic matter in the soil may help attach these cations to the organic colloids of the soils. A benefit of the soils' high CEC is that they can store a lot of nutrients, which is suitable for agriculture. This may increase crop yields and strengthen the soil's tolerance to drought (Lashari et al., 2018; Nakhli et al., 2017; Senesi and Loffredo, 2018). The high CEC can, however, be problematic because it increases the susceptibility of the soils to salinization (Nabiollahi et al., 2017). This is the case because the high CEC can bind to cations like sodium and chloride ions. Over time, these ions may build up in the soil and cause it to become too salty for plants to grow in the soil (Gondek et al., 2020; Gruba and Mulder, 2015; Nabiollahi et al., 2017). The soils near Abaya and Chamo Lakes are known to have a high CEC and low variability since the CV is < 10%, which poses a complicated problem for agriculture. While it can have both favorable and adverse effects, careful soil management strategies can be used to maximize the benefits of the high CEC and minimize the risks of salinization (Sahab et al., 2021). Overall, the findings of this study were in line with the studies of EthioSIS (2016) throughout the country's woreda and kebele-level research.

3.3.12 Base saturation

According to the rating of Hazelton and Murphy, (2016), the soils of the study area are rated with very high base saturation (Table 3.5 and Figure 3.2). The percentage of the soil's CEC that is saturated by basic cations, such as calcium, magnesium, sodium, and potassium, is measured by the base saturation (BS) (Rawal et al., 2019). Having BS of 80% or higher, the BS of the soils is considered as very high in the study area. The BS was moderate as the coefficient of variation (CV) fell between 10 and 100% (Table 3.5). These high levels of base saturation and CEC are due to calcium carbonate in the soil. Regarding BS values of greater than 100%, it's essential to understand that BS measures the total cation exchange capacity (CEC) of the soil saturated with basic cations (calcium, magnesium, potassium, and sodium) (Ma et al., 2024). If the sum of these basic cations exceeds the

CEC, the BS value will be greater than 100% (Nel et al., 2023). In addition to these, if there is CaCO_3 in the soil, extracting the soil with ammonium acetate of pH 7 releases a high amount of the precipitated CaCO_3 , resulting in a higher amount of Ca that exceeds the CEC value. This can occur due to specific soil conditions, such as the presence of exchangeable sodium or other factors affecting cation exchange, which can influence the BS value (Marchuk, 2013).

Calcium carbonate is a basic mineral that helps neutralize acidity and makes the soil more alkaline. This is important for agriculture, as most crops prefer slightly acidic to slightly alkaline conditions (Msimbira and Smith, 2020; Riaz et al., 2020; Tiecher et al., 2023). The high base saturation and CEC in the soils of the study area also indicate that the soils could be more saline. Salts accumulate up in the soil, causing salinity, and these salts can be detrimental to crops (Zaman et al., 2018). However, the high levels of basic cations in the study area help bind the salts and prevent them from accumulating (Yang and Guo, 2018). Overall, the soils of the study area have excellent CEC and base saturation, resulting in a good location for agriculture.

3.3.13 Available potassium

The range of K concentrations, from 346.49 to 714.38 mg kg^{-1} , shows substantial variations in the potassium levels that are readily available (Table 3.5). The mean K concentration of 574.48 mg kg^{-1} indicates that a lot of potassium is readily available in the surface soil. The range of the available potassium concentration in the subsurface soil, 344.29 to 747.78 mg kg^{-1} with a mean of 516.89 mg kg^{-1} , is slightly lower than that of the surface described above (Table 3.5). Compared to the surface soil, the subsurface soil had relatively lower concentration of potassium that is readily available. The variability of the available potassium was moderate as the coefficient of variation (CV) fell between 10 and 100%.

Overall, these findings show very high levels of potassium availability in the agricultural soils surrounding Abaya and Chamo Lakes in the South Ethiopian Rift Valley, especially in the surface soil according to Jones (2004) (Figure 3.2). Because soils have accumulated sodium (Na^+) and potassium (K^+) salts, when there is low rainfall and high evaporation, water rises through the soil, bringing dissolved salts to the surface and causing accumulation in those areas. Since potassium is an essential nutrient for plants, high potassium availability may be advantageous for crop growth and productivity (Jaiswal et al., 2016). Potassium levels must be carefully managed to avoid excessive

accumulation, which can have detrimental effects on soil fertility and environmental sustainability (Osman and Osman, 2018). Excess potassium can reduce the availability of other nutrients like magnesium, calcium, and boron. This can lead to nutrient deficiencies, impacting plant growth and health (Abbas et al., 2021). Also, high potassium levels can cause clay particles to disperse, leading to soil compaction (Lipiec et al., 2018).

3.3.14 Organic carbon

The organic carbon (OC) content of the surface soils (0–20 cm depth) varied from 0.54 to 1.32%, with a mean of 1.02% (Table 3.5). Whereas the subsurface soil's (20–40 cm depth) organic carbon (OC) content ranged from 0.45% to 0.90% and had a mean value of 0.70. These values fall below the 1.5% OC threshold (Figure 3.2), and considered as low OC content (Wogi et al., 2021). This revealed that results similar to past studies were similar to the findings of previous research studies (EthioSIS, 2016). Reduced crop yield, increased susceptibility to erosion, degradation in the health of the soil, and an increased risk of soil salinity are just a few of the detrimental effects that low OC content can have in soils (Haj-Amor et al., 2022). Its coefficient of variation was rated moderate for both surface and subsurface soils since it is between the 10 to 100 CV% range. Agricultural soils must be managed to increase their OC contents and reduce the negative effects of low OC. Cover crops, mulching, adding organic material, crop rotation, minimum tillage, and other management techniques (like crop residue retention, biochar application, conservation agriculture, agroforestry system, and reduced grazing) can increase the OC content in the soil (Francaviglia et al., 2023; Garcia-Franco et al., 2021). These management techniques can help restore the productivity and health of soils by increasing their OC content (R. Kumar et al., 2022).

3.3.15 Total nitrogen (TN)

The total nitrogen (TN) content of the experimental soils ranged from 0.03 to 0.06% in the surface soil (0-20 cm depth) and from 0.01 to 0.06% in the subsurface soil (20-40 cm depth), with mean values of 0.04% and 0.03%, respectively (Table 3.5). The coefficient of variation of total nitrogen (TN) was rated moderate for both surface and subsurface soils since it is between the 10 to 100 CV% ranges. The soil quality standards and interpreting guidelines developed by Landon (2014) define this TN level as a very low (Figure 3.2). Farmers in this area should apply nitrogen fertilizers to increase crop yields (Phung et al., 2020; Qiao et al., 2021). However, you must understand that too much

nitrogen fertilizer can harm the environment. Therefore, to achieve the desired crop yields without harming the environment, it is crucial to carefully balance the amount of nitrogen fertilizer applied to the soil (Aczel, 2019; Bijay, 2018). Notably, a limited number of locations near Abaya and Chamo Lakes were used to measure the TN levels in the study. Other areas of the region may have different TN levels. To ascertain the actual TN levels and other nutrient deficiencies, conducting soil testing in other places where crops are grown is crucial (Liu et al., 2017). Using this knowledge, a fertilizer management strategy that maximizes crop yields while maintaining the environment is feasible. In general, the findings of this study were similar to past studies and those of EthioSIS, (2016), which rated the TN of the soils as low.

3.3.16 Calcium carbonate (CaCO₃)

The study area had mean calcium carbonate contents (CaCO₃) of 2.54% and 2.12%, in the surface and surface layers respectively. The values ranged from 0.80 to 3.80% in the surface soil (0-20 cm depth) and from 0.20 to 3.40% in the subsurface soil (20-40 cm depth) (Table 3.5). Calcium carbonate (CaCO₃) content of less than 3.5% is considered as low, in accordance with FAO and ISRIC (2012). The calcium carbonate content in the agricultural soils of the study area is lower than this threshold. Overall, this study's results were consistent with those of other researches that rated low level of calcium carbonate in the soils of the study area (EthioSIS, 2016). A possible reason for the low level of CaCO₃ is that precipitation mixes with bicarbonate ions. This mixing can happen when conditions prevent the reaction between calcium and bicarbonate ions. Factors like low calcium ion concentration or high temperature can contribute to low CaCO₃ levels. The nature of the parent material and the quality of the irrigation water might have been the cause of the CaCO₃ variance (Rezapour et al., 2017). The CaCO₃ content's coefficient of variation was deemed moderate for both surface and subsurface soils due to its value falling within the range of 10 to 100 CV%. CaCO₃ accumulation in soils indeed tends to occur at higher pH levels (above 8.5). This is because the solubility of CaCO₃ decreases as pH increases, leading to its precipitation and accumulation in the soil (Laudicina et al., 2021). However, while it is true that calcium deficiency is more common in acidic soils, it is also important to note that calcium can also be deficient in high pH soils (Torres et al., 2024). This can happen due to imbalances with other cations: Excesses of other cations, such as sodium or magnesium, can compete with calcium for absorption sites in the soil, limiting its availability (Fageria et al., 2011; Lambers et al., 2019). The growth of plants may be affected in

several ways by this low calcium carbonate content. These reduce calcium uptake, altered soil pH, physiological disorder, reduced root growth, and increased sustainability to disease (Ghorbani et al., 2008; Taalab et al., 2019). A crucial nutrient for plants, calcium carbonate additionally helps better the drainage and structure of the soil (Durand et al., 2018). Plants may be unable to obtain the calcium they require when calcium carbonate levels are low, which can limit the availability of calcium ions in the soil, hindering their uptake. They may also be more vulnerable to waterlogging and other problems (Taalab et al., 2019). Low levels of calcium carbonate can make soil more acidic, which harms plant growth. Calcium carbonate helps keep the soil pH balanced, preventing it from becoming too acidic. In acidic soils, other essential nutrients like phosphorus and magnesium can become less available to plants (Msimbira and Smith, 2020; Vista et al., 2024).

Table 3. 5: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

Depth	Des. S	CEC	BS	Av.K	OC	TN	CaCO ₃
		(cmolckg ⁻¹),	%	(mg kg ⁻¹)		%	
0 – 20 cm	Mean	49.74	125.40	574.48	1.02	0.04	2.54
	SD	2.36	27.84	141.39	0.30	0.01	1.19
	Minimum	46.00	83.00	346.49	0.54	0.03	0.80
	Maximum	52.10	154.00	714.38	1.32	0.06	3.80
	CV%	4.74	22.20	24.61	29.32	26.07	46.88
20 – 40 cm	Mean	47.36	126.60	516.89	0.70	0.03	2.12
	SD	2.23	35.99	156.50	0.18	0.02	1.20
	Minimum	45.20	86.00	344.29	0.45	0.01	0.20
	Maximum	50.70	163.00	747.78	0.90	0.06	3.40
	CV%	4.72	28.43	30.28	25.50	53.44	56.74

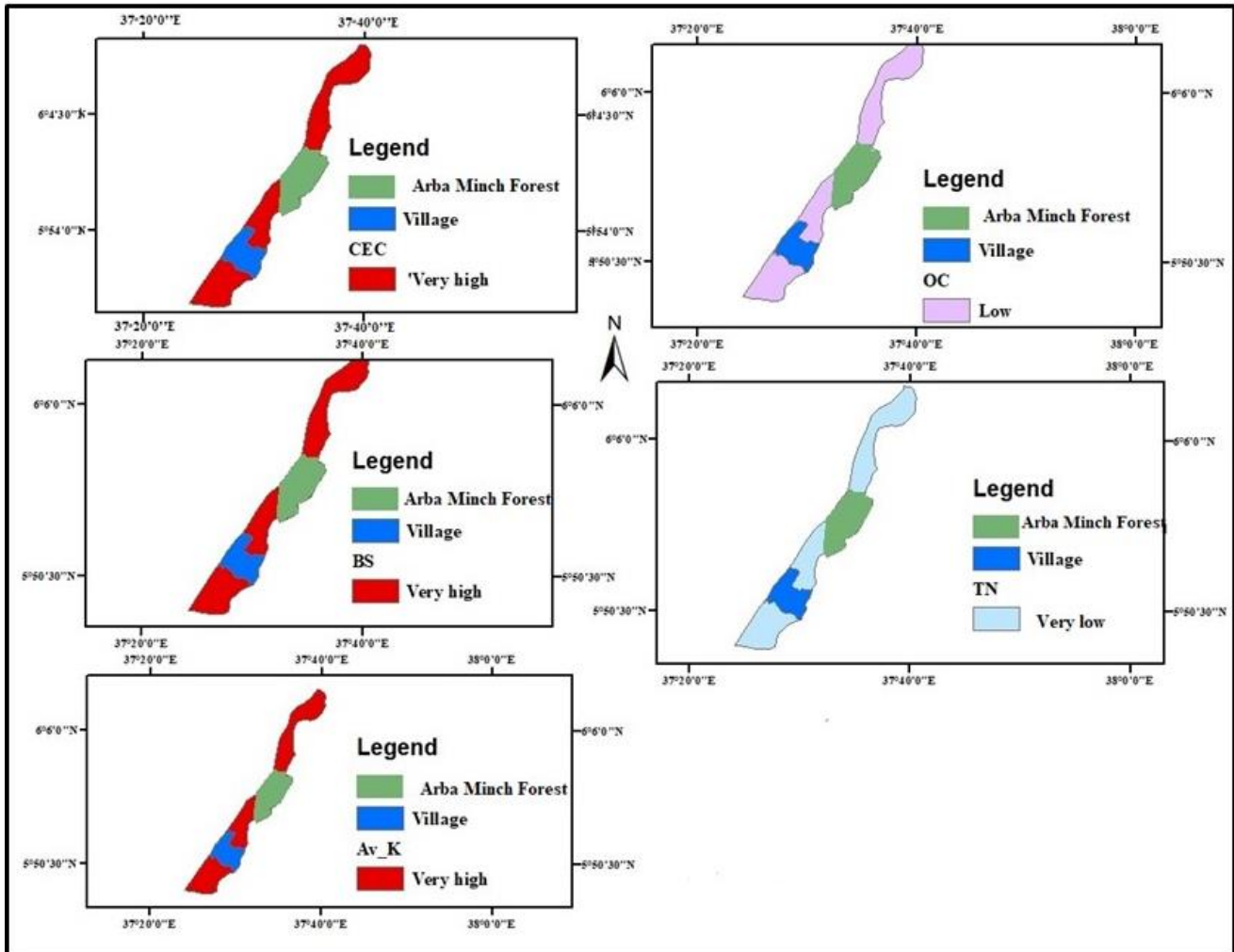


Figure 3. 2: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

3.3.17 Available iron

Iron is a crucial micronutrient for plants' various metabolic processes throughout their life cycle (Rout and Sahoo, 2015; Tripathi et al., 2015). The experimental soils had very high levels of available iron (Table 3.6). In the surface soil (0–20 cm depth), the amount of iron was 14.54–176.02 mg kg⁻¹; in the subsurface soil (20–40 cm depth), it was 13.99–57.51 mg kg⁻¹. The mean quantities of available iron were 61.78 and 25.79 mg kg⁻¹ in the surface and subsurface soils respectively (Table 3.6). These are very high threshold (50 mg kg⁻¹) set by Wogi et al. (2021) (Figure 3.3).

The findings of this study generally agreed with those of prior investigations that rated high iron levels (EthioSIS, 2016). Alkaline soils, frequently affected by salt, can bind iron in the soil and reduce

its availability to plants. However, iron availability in these soils doesn't seem to be the high pH since most iron availability is expected in low pH conditions (Martínez-Cortijo and Ruiz-Canales, 2018).

Naturally soils have waterlogging which can increase the available iron content in salt-affected sodic soils (Chhabra and Chhabra, 2021). This is because waterlogging can displace the sodium ions that are bound to the iron in the soil, making the iron more available to plants. This makes the iron more available to plants, which can help improve their iron status (Rengel, 2023). Generally, an important factor influencing the amount of soluble Fe in the soil solution is the oxidation-reduction process. But in the case of waterlogged fallow it has less influence since lowering redox reaction increases Fe^{2+} solubility (Xie et al., 2022). In soils, there is very low Fe^{3+} in the solution. The concentration of Fe^{2+} in solution is lower in well-drained, oxidized soils Fe^{3+} the dominating species. Soluble Fe^{2+} increases significantly when the soil become waterlogged (Hewitt et al., 2021; Kögel-Knabner et al., 2010). The high level of iron present in the soil of the study area is great news for the farmers in the region. This indicates that their crops will have access to sufficient iron, which is essential for the growth and development of plants. However, it is important to note that too much iron can also be harmful to plants. Therefore, it is advisable to periodically test their soil to ensure that the iron level is optimal for their crops (Rehman et al., 2021; Rout and Sahoo, 2015; White and Broadley, 2009; Willy et al., 2019).

3.3.18 Available manganese

Manganese is a vital micronutrient for plants, playing a key role in many metabolic processes such as being an antioxidant cofactor for enzymes and in photosynthetic processes (Kwakye and Kadyampakeni, 2022). The available manganese content ranged from 17.95 to 79.44 mg kg^{-1} in the surface soil (0-20 cm depth) and from 13.98 to 45.37 mg kg^{-1} in the subsurface soil (20-40 cm depth) (Table 3.6). The available manganese level in the study soils is very high (Figure 3.3) in accordance with Wogi et al. (2021). In general, this study's results align with those of earlier studies that found high levels of manganese (EthioSIS, 2016). The mean available manganese levels were 32.08 and 23.53 mg kg^{-1} in the surface and subsurface soil respectively (Table 3.6). The high level of available manganese in these soils is likely due to the high salinity of the soils. Salinity can increase the availability of manganese by displacing it from the soil particles through cation exchange (Bhatla et al., 2018). Positively charged ions, such as manganese (Mn^{2+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+), are attracted to these negatively charged surfaces. These cations

compete with each other for binding sites on the soil particles (Rajamuthuramalingam et al., 2024). As manganese is released into the soil solution, it becomes more readily available for plant uptake (Rengel, 2015). This can lead to manganese toxicity in plants, which can manifest as stunted growth, chlorosis, and necrosis (Bhatla et al., 2018).

The soil quality standards and interpreting guidelines developed by Wogi et al. (2021) define a very high level of available manganese as $> 6 \text{ mg kg}^{-1}$. These high levels of Mn are most likely manganese due to the release of Mn under waterlogged salt-affected soil, typical fermentation byproducts. This microbial metabolic process occurs when oxygen levels are very low and degrades humus into simpler organic compounds while producing H_2 and CO_2 . In the soil solution, the reported concentrations of acetate (millimolar) and H_2 gas (micromolar) are typical of active fermentation (Nivethadevi et al., 2021; Steger et al., 2017; Thampatti, 2022). The accumulation of these fermentation products during the initial stages of incubation is followed by their depletion as Mn(II) levels rise or methane production starts, indicating consumption by the microbial community during these stages (Huan et al., 2018). Soil waterlogging will reduce O_2 and reduce redox potential, increasing soluble Mn^{2+} . Mn availability can be increased by poor aeration in compacted soils and by local accumulation of CO_2 around roots and other soil microsites (Jennings, 2007). The resulting low redox condition will render Mn more available without appreciably affecting the redox potential of the pH of the bulk soil.

Generally, the level of manganese in these soils is not at the toxic level, but it is getting close (Maguffin et al., 2020). The high level of readily available manganese must be recognized, and measures must be taken to reduce the possibility of toxicity. The two potential remedies are altering the crop variety to one that can tolerate manganese toxicity or adding chelating agents to the soil to bind the manganese (Dhaliwal et al., 2023; Neal and Zheng, 2015).

3.3.19 Available zinc

Zinc deficiency is an important micronutrient barrier to food production in every region of the world, and its application has been successful in almost all crops (Younas et al., 2023). The amount of readily available zinc in the surface soil (0–20 cm depth) ranged from $0.63\text{--}1.04 \text{ mg kg}^{-1}$, whereas in the subsurface soil (20–40 cm depth), it ranged from $0.08\text{--}0.99 \text{ mg kg}^{-1}$ (Table 3.6). There is little readily available zinc in the study soils (Figure 3.3). The mean concentration of available zinc in soil is 0.80

mg kg⁻¹ in surface soil and 0.55 mg kg⁻¹ in subsurface soil. According to Mantovi et al. (2003), the normal range for zinc in the soil is 1.5 to 6 mg kg⁻¹. These high salinity of the experimental soils could be the probable reason for the low concentration of readily available zinc.

The results of this study were nearly consistent with those of prior studies that found optimum zinc levels (EthioSIS, 2016). Zinc can form insoluble compounds by reacting with carbonate and hydroxide ions in soils at high pH levels. This can lead to a reduction in plant availability of zinc. Soil salinity can also limit zinc availability by decreasing microbial activity, which is responsible for releasing zinc from organic matter (Andrunik et al., 2020; Baruah, 2018; Suganya et al., 2020). By attaching zinc to soil particles, salinity can reduce zinc availability (Acosta et al., 2011). Zn²⁺ and soil organic matter (OM) components also form stable complexes. Zn availability will be decreased during immobilization reactions; this happens in soils with humic peat deficiencies. These may be why a soil with a healthy amount of organic matter has a zinc deficiency (Laurent et al., 2020; Suganya et al., 2020).

On the other hand, keeping Zn²⁺ in solution will improve availability by forming soluble chelated Zn compounds. Freshly applied organic matter and its constituents can chelate Zn²⁺, though this ability is not always reflected in improved Zn uptake by plants. According to the soil quality standards and interpretation guidelines developed by Wogi et al. (2021), a low level of available zinc is less than 1.0 mg kg⁻¹. Therefore, the study soils have significantly lower level of zinc availability than the indicated threshold. It is therefore critical to be aware of the limited zinc supply and take precautions against its deficiency. This might involve applying fertilizer with zinc to the soil or using a cover crop that resolves zinc deficiency (Mustafa et al., 2022).

3.3.20 Available copper

Copper is a crucial micronutrient for the growth and development of plants, but it may also be toxic at high concentrations (Ali et al., 2020). In the surface soil (0–20 cm depth), the amount of copper that was readily available ranged from 3.19 to 10.88 mg kg⁻¹, and in the subsurface soil (20–40 cm depth), it ranged from 2.21 to 6.85 mg kg⁻¹ (Table 3.6). There is a readily available and very high concentration of copper in the study soils (Figure 3.3). The surface soil (0–20 cm depth) and the subsurface soil (20–40 cm depth) had mean available copper levels of 5.22 and 3.82 mg kg⁻¹, respectively (Table 3.6).

This study's findings in line with other research rating optimum copper levels (EthioSIS, 2016). The high concentration of copper in the agricultural soils of the study area could be attributed to the abundance of copper-rich volcanic rocks in the region due to their volcanic origin (Hua et al., 2021). Additionally, the alkaline soils, with a higher pH and their high clay content create favorable conditions for the retention of copper in the soil (Kome et al., 2019). Over time, copper is gradually released from these rocks through weathering and builds up in the soil, leading to high levels of available copper that can cause harm to animals, humans, and plants (Hough, 2010; Izydorczyk et al., 2021).

In most soils, the copper content ranges from 2 to 100 mg kg⁻¹, with an average value of about 30 mg kg⁻¹, and hence the values obtained from the results fall within the normal range (Panagos et al., 2018). According to Bhatla et al. (2018), most of this could be in unavailable mineral form, and it may even pollute water bodies. Following the standards and interpretation guidelines, developed by Wogi et al. (2021) Cu content greater than 3 mg kg⁻¹ is as very high available copper level. There are various ways to reduce the quantity of available copper in the soil. One of these is to remove the copper-rich rocks from the region. Another option is to add organic matter to the soil, which helps bind the copper and decrease its availability to plants and animals. The high level of readily available copper can pose a significant risk to the environment and can have a negative impact on agriculture (Alengebawy et al., 2021; Tóth et al., 2016; Van der Ent and Reeves, 2015; Vinod et al., 2021). It is therefore crucial to monitor the amount of available copper in the soil and take necessary measures (remove the copper-rich rocks from the region and add organic matter to the soil, which helps bind the copper and decrease its availability to plants and animals), to reduce it.

Table 3. 6: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

Depth	Des. S	Fe	Mn	Cu	Zn
		mg kg ⁻¹			
0 – 20 cm	Mean	61.78	32.08	5.22	0.80
	SD	68.74	26.54	3.21	0.17
	Minimum	14.54	17.95	3.19	0.63
	Maximum	176.02	79.44	10.88	1.04
	CV%	111.25	82.73	61.63	21.19
20 – 40 cm	Mean	25.79	23.53	3.82	0.55
	SD	17.88	12.47	1.77	0.32
	Minimum	13.99	13.98	2.21	0.08
	Maximum	57.51	45.37	6.85	0.99
	CV%	69.32	52.99	46.33	58.61

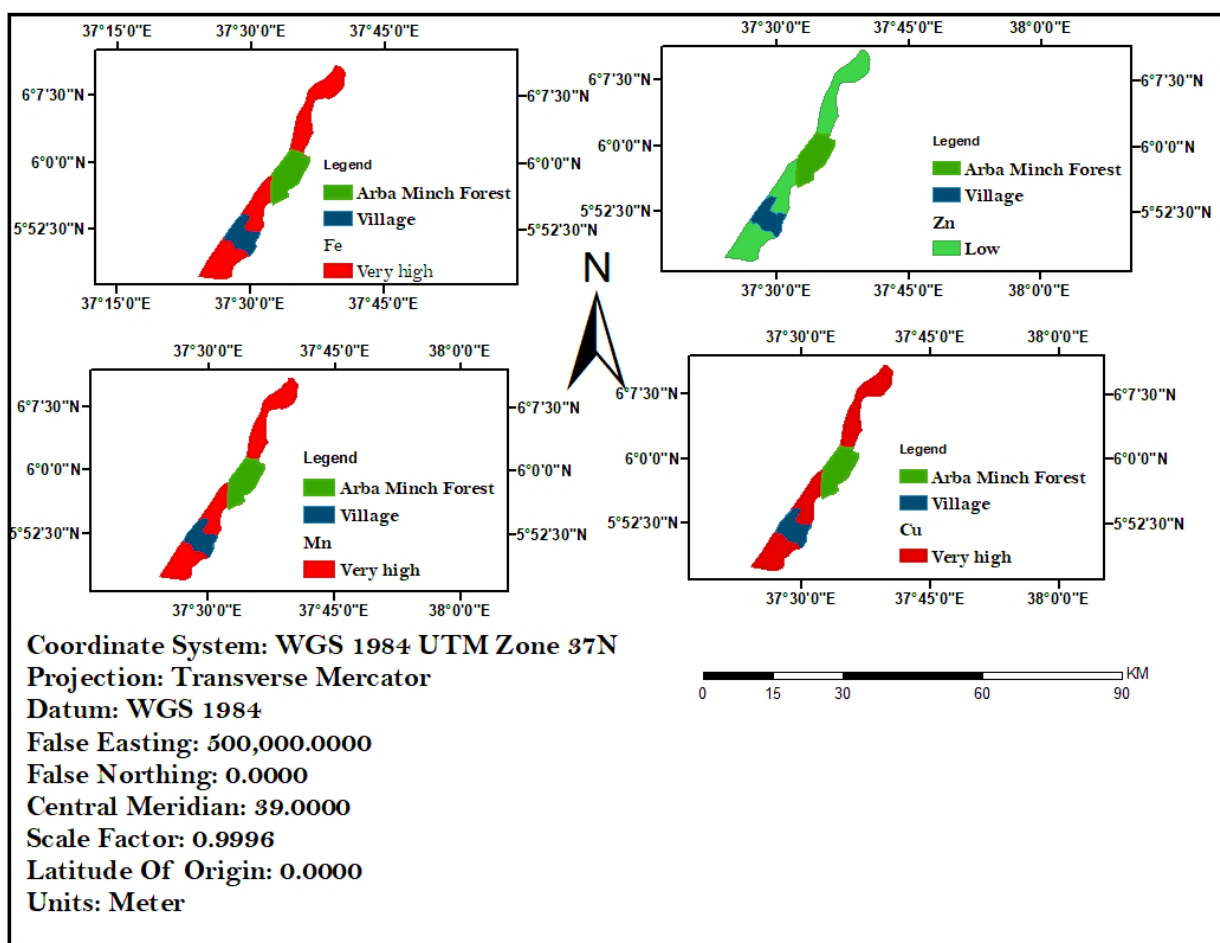


Figure 3. 3: Soil fertility status of agricultural soils around Abaya and Chamo Lakes

3.3.21 Site-specific nutrient management, and reclamation strategies

Most of the study areas were rated with deficient total nitrogen, considering that a very low amount of nitrogen in the soil is available to plants. Hence, the plants may still require nitrogen fertilizer to produce maximum yields (Anas et al., 2020). Based on the findings from the present study, we recommend external application of nitrogen fertilizer in the study area (Figure 3.4). The site-specific recommendation for fertilizer application was different from that of EthioSIS (2016) except for the nitrogen fertilizer recommendation, which was Nitrogen-Phosphorous-Sulfur fertilizer (NPS) and potash fertilizer. In the present study however, phosphors, and potassium were ideal in the study area and should not be included in the fertilizer recommendation. Therefore, the available sulfur must be assessed and recommended for future studies. This made the present study quite different from previous studies of EthioSIS (2016). According to Sultana et al. (2015), the crop being grown, the expected yield, and the soil N test results will all influence how much nitrogen fertilizer is required. Organic matter levels are low in the salt-affected agricultural soils in the study area. According to Tarafdar (2022), organic matter helps improve soil structure, water retention, nutrient availability and soil health. The salinity of the soil is also decreased with application of organic materials (Bello et al., 2021).

The soils around Abaya and Chamo Lakes that have been adversely affected by salt and can be improved by applying organic matter. By absorbing sodium ions and other salts, it can help improve the soil structure, increase the soil's ability to retain water, increase the availability of nutrients, and decrease the salinity of the soil (Bedadi et al., 2023). The low to medium exchangeable calcium rating in the soils of the study area suggests the soils may need more calcium for optimal plant growth (Behera and Shukla, 2015). Similarly, the low zinc availability warrants precautions against its deficiency, highlighting the need for an adequate nutrient supply (Choudhury and Moulick, 2022). The agricultural soils around Abaya and Chamo Lakes have an alkaline pH. Organic matter and gypsum can improve soil structure and reduce pH (Walche et al., 2023, 2024).

The high rate of exchangeable sodium in the area can be reduced through management practices like gypsum application, leaching with quality water, and phytoremediation (Bedadi et al., 2023). According to FAO (2020), the majority of the soils in the study area is classified as sodic soils and need reclamation (Figure 3.4). Reclamation of sodic soil is a difficult process that can take years to complete (Li and Kang, 2020). The ideal reclamation plan will change based on the particular soil

characteristics, the desired crops to be grown, and the available resources (Hopmans et al., 2021). Combining these techniques is the best way to reclaim sodic soils. A specific combination of strategies will be employed based on the particular soil conditions and the desired crops to be grown (Daba and Qureshi, 2021). Although it is difficult, sodic soils can be reclaimed and made productive again. The physical and chemical characteristics of sodic soils can be enhanced, making them suitable for crop cultivation, by following the suggested reclamation strategies (Gangwar et al., 2020).

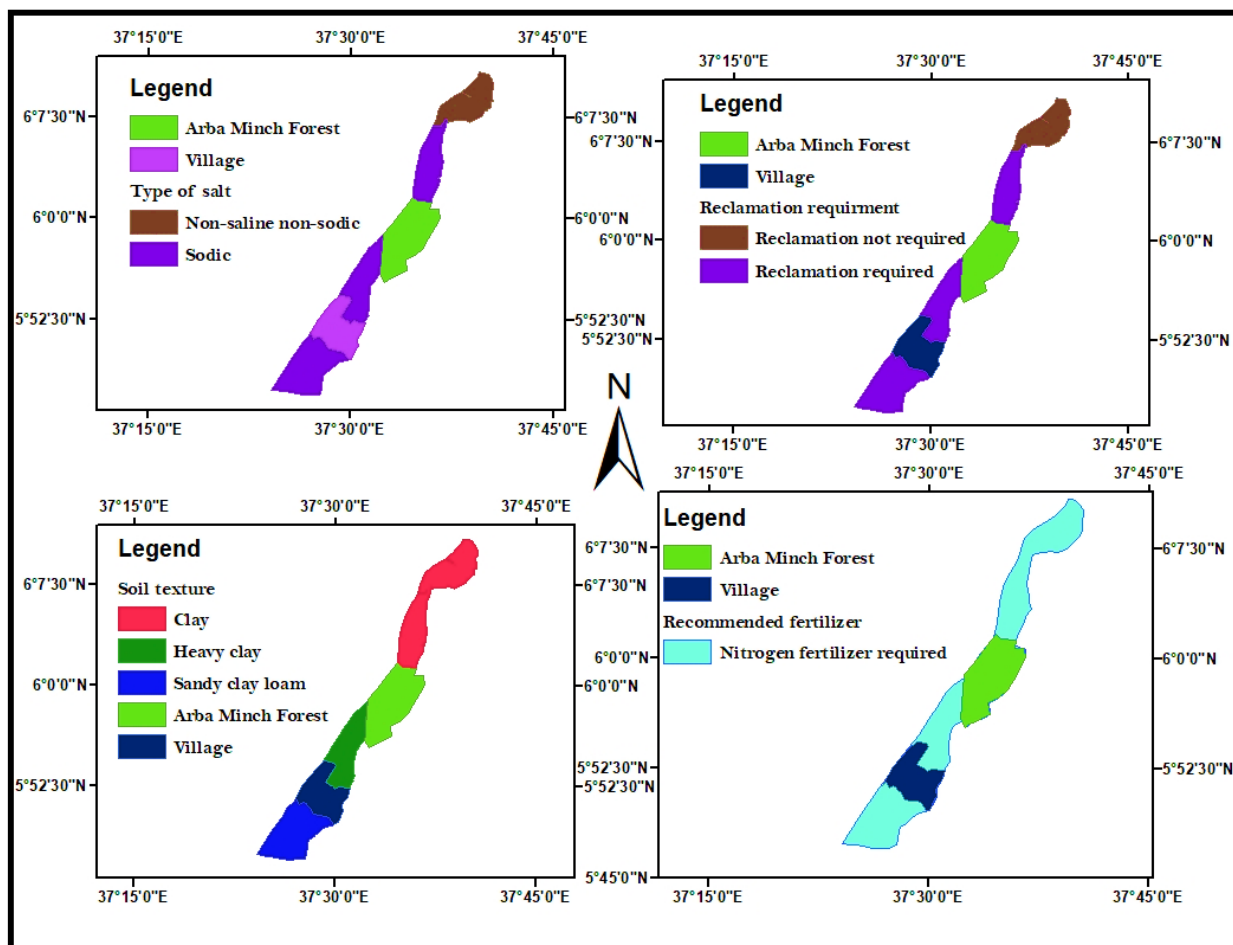


Figure 3. 4: Map of type of salt, soil texture, recommended reclamation requirements, and recommended fertilizer requirements of agricultural soils around Abaya and Chamo Lakes, respectively

3.4 Conclusion

The study analyzed soil properties and assessed the fertility status of soils around Abaya and Chamo Lakes, Southern Ethiopia Rift Valley, for successful crop production and land use planning. The study found soil textural classes like clay, heavy clay, and sandy clay loam, with dark brown to black color, angular blocky structure, and heterogeneity. Surface soil had higher AWHC, alkaline pH, and low exchangeable calcium. The soils of the study area, with a high exchangeable sodium percentage ranging from 94% to 99%, may negatively affect crop production. The study found surface soil has higher phosphorus content due to weathering and decomposition, high soil CEC, high potassium availability, low organic carbon, very low total nitrogen content, and high iron, manganese, and copper levels. It's critical to recognize that mapping soil fertility is a dynamic process. Agricultural practices, climate, and land use can all affect soil conditions. As a result, comparing this current research with EthioSIS (2016) offers critical new perspectives on these developments. The current study results thus make it possible to evaluate how soil nutritional availability has changed throughout time. This might show where there has been a slow decline in soil fertility. Routine soil testing and mapping should be implemented to track changes in soil fertility status over time. The EthioSIS data should be updated and improved using the new information to keep it accurate and valuable. Ethiopia may manage soil fertility, improve yields from agriculture, and ensure food security through implementing the recommendations into practice. Despite having fertile soil, the study area may require additional fertilizer application for deficient nutrients and reclamation for salt-affected areas for optimal crop yield.

3.5 References

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4. SPATIAL ANALYSIS AND MAPPING OF THE INTENSITY AND TYPES OF SALT-AFFECTED SOILS AROUND ABAYA AND CHAMO LAKES, SOUTHERN ETHIOPIAN RIFT VALLEY

Azmera Walche, Wassie Haile, Alemayehu Kiflu, and Dereje Tsegaye

ABSTRACT

*Salt-affected soils have significant enough salt concentrations to impact other land and soil resource uses, plant health, soil characteristics, and water quality. Consequently, a study was carried out in the area of the South Ethiopian Rift Valley around the lakes of Abaya and Chamo to determine the types and intensity of soil affected by salt and map their spatial distributions. At 0–20 cm depths, a grid soil sampling scheme was employed to gather data from agricultural salt-affected soils. An adequately spaced grid cell of 200 m*200 m or seven transects, with seven samples collected every 200 meters on each sampling site, was generated by the QGIS software's Fishnet tool, and 226 soil samples were collected using an auger from the proposed 245 soil sampling points. The analysis and interpretation of the data were done using both statistical and geostatistical methods. The un-sampled surface was predicted and mapped from laboratory point data using the standard Kriging algorithm in QGIS. The soils of the study area were rated as strongly alkaline (8.5-9.0) and moderately alkaline (7.9-8.4) in the reaction. The coefficient of variation (CV) for soil pH, was the lowest and such low CV (<10%) confirmed the similarity of pH values throughout all research areas, except for the Ganta Kanchama site. The EC values depicted that the salt-affected soils of the study area are slightly saline (0.75-2 dS m⁻¹), except for the Ganta Kanchame site, which were rated as moderately saline (2-4 dS m⁻¹) to strongly saline (4-8 dS m⁻¹). The distribution of exchangeable sodium percentage (ESP) values among the study sites demonstrated considerable variability and differences. The area is dominated by low (<5%) to high-risk (>15%) rate soil sodicity, as evidenced by the soil ESP values of the studied area, and showed significant variability among the samples (CV >100%). Out of 2274.65 ha of the studied area, 62.28%, 26.09%, 10.99%, and 0.63% were categorized as non-saline non-sodic, saline-sodic, sodic, and saline, respectively. Non-saline and non-sodic salt-affected soils comprised most of the investigated area. The result indicated almost all the salt-affected areas were situated in relatively lower slope areas having a flat to almost flat slope (0-2%). The findings suggest that the studied area needs specific soil management strategies to reduce the salinity and sodicity problems around the study area and recommended reclamation techniques as the extent of the problems.*

Keywords: Agricultural salt-affected soils, semi-arid region, geostatistical methods, intensity of salt problems, types of salt

4.1 Introduction

Different proportions of salt-affected soils affected by salts can be found across all continents. Globally, salt-affected soils are a concern that lowers crop yields, soil sustainability, and cultivable land area (Dagar et al., 2019; FAO, 2020; Negacz et al., 2022). Salt-affected soils are those with significantly enough salt concentrations to have an impact on land and soil resource uses, plant health, soil characteristics, and water quality (Dagar et al., 2019). According to some academics (eg., Chhabra and Chhabra, 2021), salt-affected soils that have high exchangeable sodium (sodicity), soluble salts, or both in proportions can impede the growth and development of plants.

In many nations, soil salinity and sodicity are the two main obstacles to agricultural production, which result in large losses in land degradation and crop yields (Adane et al., 2019; Daba and Qureshi, 2021b). For instance, according to Dagar et al. (2019), more than 120 nations worldwide have salt-affected soils, which vary in extent, nature and properties. Salinization currently poses a hazard to about 7% of the world's land area (Okur and Örcen, 2020). According to a review of the global soil salinity by Chhabra and Chhabra, (2021), 835 million hectares of land worldwide are affected by salt, with varying regional distributions. Prāvālie (2016) stated that the problem of soil salinity is getting worse in North Africa, East Africa, the Middle East, East Asia, and South Asia, and it will get even worse in nations like America, China, Hungary, and Australia.

It is commonly known that salt-affected soils occur across Ethiopia. The areal extent of salt-affected soils encompasses 11,033,000 hectares of land in Ethiopia, most of which are located in the rift valley zone. Similarly, the land areas around Abaya and Chamo Lakes and Alage district are impacted by salts (Alemayehu et al., 2016; Asmamaw et al., 2018; Habtamu and Wassie, 2022; Walche et al., 2023). Soil salinization is a major environmental issue that can arise from both natural and human activity. High salt concentrations in parent materials or ground water result in primary salinization, a naturally occurring phenomenon that causes salts to build through natural processes (Okur and Örcen, 2020; Ondrasek and Rengel, 2021; Parvaiz et al., 2021). According to Tessema et al. (2023), secondary salinization is a frequent result of excessive watering because of poor irrigation practices, poorly managed irrigation infrastructure, inadequate soil internal drainage, and improper irrigation water quality.

Soil salinization is caused by soluble salts' upward movement and accumulation at or near the soil surface, which is facilitated by ground water (Yin et al., 2022). Salts in the soil are transported with soil moisture by capillary action and become a cause of saline soil development when the water table is near the soil surface and the evaporation rate is high (Shokri-Kuehni et al., 2020; Zewdu et al., 2017). In agricultural salt-affected soils, evapotranspiration causes salts to accumulate up in the root zone. This is because salts are left behind when water evaporates selectively through evapotranspiration (Yin et al., 2023). Moreover, poor irrigation water quality, low soil permeability or a high water table can cause poor drainage (Singh, 2019), and topographic factors can also cause an upslope recharge to cause a downslope outflow of salts, all of which can lead to an accumulation of soil salinity (Daneshmand et al., 2020). Based on research by Daba and Qureshi (2021a); Hopmans et al. (2021), and others, development of soil salinity and sodicity is generally a dynamic process with significant consequences for the soil, hydrological, agricultural, climatic, geochemical, social, and economic aspects.

Soil salinity and sodicity are highly dynamic and varied spatially over time. A key management problem is the heterogeneity of the soil, which is primarily imposed by the mosaic distribution of salt and sodicity (Ferreira et al., 2022). Different approaches to management and rehabilitation are predetermined by this variability. To enable site-specific management systems, spatial prediction, database setting up (Nyéki et al., 2021), and making digital maps of soil salinization and sodification patterns that can be used for action is very crucial (Omuto et al., 2022). Since the goal of developing and implementing successful soil reclamation programs is to prevent or reduce soil salinity and sodicity, data regarding the spatial extent, character, and distribution of soil salinity is becoming more and more crucial (Günel, 2021). For agricultural management to be effective and support site-specific management decisions, timely detection of soil salinity and sodicity as well as mapping of the spatial distribution and severity of salinity are crucial (Singh, 2022). Prior to attempting any reclamation operations, mapping the types of salt-affected soils (saline, saline-sodic, and sodic) is the first step, as reclamation processes vary depending on the nature of the problem or its severity (Laiskhanov et al., 2023). The two most popular GIS spatial interpolation techniques for forecasting and creating the spatial distribution map of soil properties like salinity are inverse distance weighting (IDW) and ordinary kriging (Chhabra and Chhabra, 2021). Kriging is an accurate geostatistics technique that is commonly applied in various fields, including soil science (Aredehey et al., 2018; Oliver and Webster, 2015).

Walche et al. (2023) found that the salt-affected soils in the Southern Ethiopian Rift Valley surrounding Abaya and Chamo Lakes are prone to salinity and sodicity. Previous studies in this area are few and have primarily concentrated on soil fertility maps for fertilizer recommendations (EthioSIS, 2016), taxonomic classification, soil characterization (Zebire et al., 2019), and related topics due to the need for precise data regarding the extent and distribution of salt-affected soils in the region. Agricultural productivity and environmental sustainability are seriously compromised by salt-affected soils, defined by high concentrations of soluble salts. It is essential to map the geographic distribution of salt-affected soil of the study area and determine their current conditions. Mapping these salt-affected soils provides a comprehensive understanding of their spatial distribution and extent, facilitating well-informed decision-making and resource allocation for restoration and management alternatives.

Thus, controlling and repairing salt-damaged salt-affected soils requires an understanding of the different forms of salts and their degree of degradation. This information can be used by researchers, land managers, and decision-makers to effectively address salt problems and promote sustainable and ecologically friendly farming methods. By reclaiming the research area, future salinization and sodicity problems would be lessened, preserving the agricultural grounds. As a result, the present study was initiated to assess the intensity and types of salt-affected soil and map their spatial distribution patterns around Abaya and Chamo Lakes South Ethiopian Rift Valley and contribute to the protection and reclamation of soil salinity/sodicinity, thereby supporting site-specific soil management tasks, strategies, and intervention.

4.2 Materials and Methods

4.2.1 Descriptions of the study area

The study area description was similar to the one mentioned in the introduction of this dissertation paper (section 1.3). Still, the specific sampling sites were selected based on the findings of the first article of Walche et al. (2023), which suggested detailed salinity and sodicity studies on the type, intensity, and distribution to specific sampling sites were recommended, to apply the reclamation strategies in the study area. Accordingly, the Omo Lante, Lante, and Abulo sampling sites which are located around Abaya Lake and Ganta

Kanchama, and Zeyise Elgo sampling sites located around Chamo Lakes South Ethiopia Rift Valley were considered (Figure 4.1).

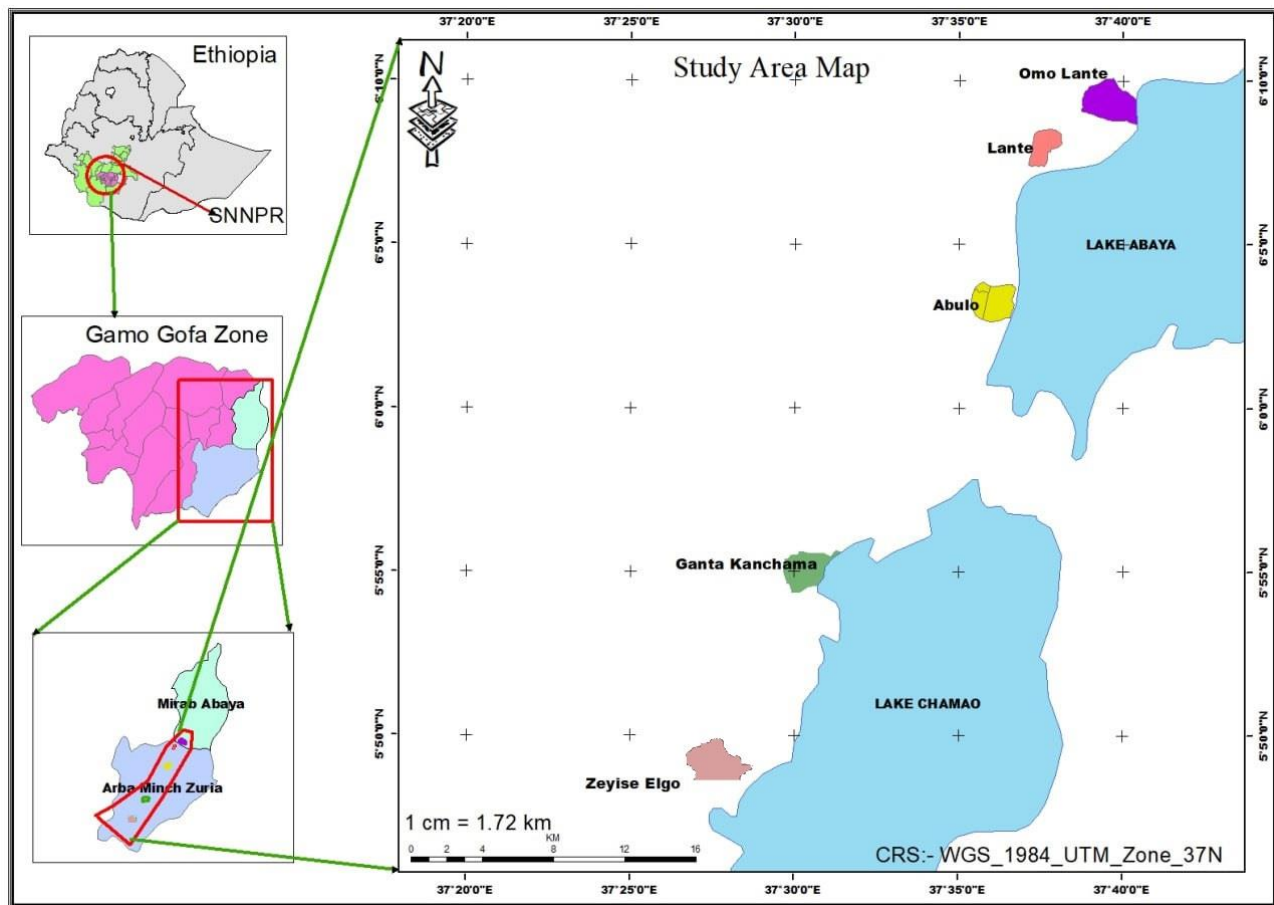


Figure 4. 1: Location map of the study area concerning sampling sites.

Where 1 represents Omo Lante sampling site, which is the boundary between Omo Lante and Fura kebeles; 2 are Lante sampling sites; 3 are Abulo sampling sites, which are the boundaries between Shara kebele, Arba Minch University demonstration farm (AMU Demo Farm), and Abulo village; and 4 are Ganta Kanchama sampling sites, which are the boundaries between Ganta Kanchama and Shele Mela kebeles; and 5 are Zeyise Elgo sampling site; SNNPR represents, South Nation Nationality People Region.

4.2.2 Material used and soil sampling procedure

Measured field data (EC, ESP, and pH), soil, landform, and other maps, as well as additional data, were used together with the digital elevation model (DEM) at a resolution of 30 meters. The investigation's Software tools include, QGIS, and Garmin GPS. The study area was demarcated from the Ethiopia Kebele administration boundary shape file and created a polygon layer for the study. A grid sampling scheme was designed, and soil samples were collected from agricultural salt-affected

soils around Abaya and Chamo Lakes South Ethiopian Rift Valley using an auger. It is one of the soil sampling strategies that deliver more information about the spatial distribution of salt-affected soils (Abdel-Fattah, 2020; Delbari et al., 2019; Srinivasan et al., 2022; Zewdu et al., 2017).

The QGIS software's Fishnet tool was utilized to create a grid of sampling points inside the polygon layer that were consistently spaced. A 200 m x 200 m grid cell was created, and nine (9) sub soil samples were taken from each grid node to make a composite. Every composite soil sample was taken within a 15-meter radius of the sampling point's center. An auger collected two hundred twenty-six (226) soil samples from 0-20cm from the proposed 245 soil sampling points by 200 m x 200 m grid cell or seven transects, with seven samples collected every 200 meters on each sampling site. We can estimate the total number of samples with the following formula: Total samples = Number of transects x Samples per transect. Total samples = seven (7) transects x 7 samples/transect, total samples = 49 samples for each sampling site, for five (5) sampling sites = $49 \times 5 = 245$. However, some sampling points fall on the mountains nearby, villages, and lakes around the sampling sites, then a total of 226 soil sampling points (Omo lante = 39, Lante = 44, Abulo = 48, Ganta Kanchama = 49, and Zeyize Elgo = 46) were used for this study (Appendix Figure 4.1). Before the field survey, the soil sampling point made by the Fishnet tool of the QGIS software was added to handheld GPS with coordinates for tracking the route and finding the sampling point. A global positioning system (GPS) was used to record the coordinates of each soil sampling point with an accuracy of ± 3 m. Samples were taken accordingly, and their absolute locations were recorded. The collected samples were put in a clean plastic tray, crushed, mixed thoroughly, and transferred 1 kg soil sample to a plastic sampling bag.

4.2.3 Soil sample preparation and analyses

The collected field soil samples were air dried laboratory temperature of 24°C in accordance with Guntiñas et al. (2012). Soil samples were mechanically crushed with a mortar and pestle after drying, and then were passed through a 2-mm mesh sieve for analysis of physicochemical properties. Following standard laboratory procedures mentioned under section 1.4., the collected soil samples were subjected determinations of particle size distribution, pH, exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) and electrical conductivity (EC). The method described under section 2.2. was used to calculate the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP). Finally, using Burt (2011) limit as a guide, the soil types affected by salt have been determined.

4.2.4 Land form

The Digital Elevation Model (DEM) of the study area was clipped from a 30 m resolution of Ethiopia in a GIS platform by masking QGIS software. The slope of the study area was generated from the Digital Elevation Model (DEM) of the study area in a GIS platform using surface analysis in QGIS software. The landform was used as one layer since landform features influence the process of salt accumulation on the soil surface due to its slope variability, which influences percolation and surface water flow (Li et al., 2014). Indirect features such as landscape may aid in identifying soil salinity and sodicity issues. The combined action of topographic factors and climate has a significant influence on the spatial distribution of soil salinity, causing variations in soil salinity and sodicity distributions, particularly in semi-arid areas (Singh, 2022; Stavi et al., 2021; N. Wang et al., 2020).

4.2.5 Cross-validation

The cross-validation was done to evaluate the accuracy of interpolation methods through mean error (ME), root mean square standardized error (RMSSE), and root means square error (RMSE). Closer values of the mean error (ME) to 0, and closer values of the root mean square standardized error (RMSSE) to 1, suggest that the prediction values are close to measured values, and hence facilitate the selection of the best-fitted semivariogram model for an interpolation map, which could provide the most accurate predictions (Nyengere et al., 2023; Yusuf et al., 2020). The spatial variability structure was assessed by calculating semivariograms in the equations mentioned in section 3.2.2.

4.2.6 Data analysis

To analyze and interpret data, both statistical and geostatistical techniques were used. To analyze soil properties, descriptive statistics data were analyzed using SAS software, version 9.4 (Blanca Mena et al., 2017). The coefficient of variation was used for the determination of soil properties variability. The variability is low when the CV is < 10%, moderate between 10 and 100%, and strong when > 100% (Terefe et al., 2021). The rating and interpretation of determined values were based on a guide to standardized analytical methodologies for soil data (Landon, 2014; Wogi et al., 2021).

The spatial distribution of salt-affected soil in the study area was determined by importing the laboratory results into a GIS environment using their corresponding coordinates (latitude and longitude) in Microsoft Excel. Using interpolation techniques, the spatial prediction and mapping of the un-sampled surface from laboratory point values were carried out in a GIS environment. From

laboratory point data, the un-sampled surface was predicted and mapped using the standard kriging algorithm in ArcGIS 10.8 (Takele and Iticha, 2020) The map of the preliminary layers of the salt-affected soil indicator, including pH, EC, and ESP, and the predicted final salt-affected soil distribution map were generated.

4.3 Results and Discussion

4.3.1 Descriptive statistics for soil characteristics around Abaya and Chamo Lakes

Soil chemical properties are essential for growth and development of different plants and crops (Pahalvi et al., 2021). Data presented in Table 1 show the statistical summary of the selected soil characteristics of agricultural salt-affected soils around Abaya and Chamo Lakes. Among the soil chemical properties analyzed, the coefficients of variation (CV) for ex. Na^+ , SAR, and ESP were strong (Table 4.1). The coefficient of variation (CV) for soil pH was the lowest (<10%) indicating the similarity of pH values in all the study areas, except for the Ganta Kanchama site which was categorized as moderate variability since the CV value is 10.46. As indicated in Table 4.1, the soil pH of the study area ranged from 7.30 to 8.57, 8.04 to 9.64, 7.73 to 9.25, 7.64 to 11.01, and 7.40 to 8.80, in the Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites respectively. According to US Salinity Laboratory Staff (1954) and (Wogi et al., 2021) rating, the results show that the salt-affected soils of the study area are characterized by non-alkaline to strongly alkaline at Omo Lante, Abulo, and Zeyise Elgo sites; and moderately alkaline to strongly alkaline at Lante and Ganta Kanchama sites respectively.

The EC values varied from 0.38 to 6.13, 0.34 to 4.68, 0.33 to 11.33, 0.74 to 25.40, 0.40 to 7.64 dS m^{-1} , in the Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites respectively. According to soil quality standards given by Landon (2014), the results show that the salt-affected soils of the study area are slightly saline except for the Ganta Kanchame site, which could be rated as moderately saline to strongly saline. The CV of soil EC for the studied salt-affected soils was between 10% and 100% for the Omo Lante and Lante sites and >100% for the Abulo, Ganta Kanchama, and Zeyise Elgo sites. Based on Terefe et al. (2021) variability, the Omo Lante, and Lante were rated with moderate variation, and Abulo, Ganta Kanchama, and Zeise Elgo sites were rated with strong variation (Table 4.1). This variation of CV values for EC is supported by the findings of Aredehey et

al. (2018), who reported that low CV approved the similarity of soil properties, and high CV ratified the variations of soil properties.

The ESP values varied from 0.30 to 19.21% with a mean value of 1.03%; 0.73 to 25.31% with a mean of 2.14%; 0.24 to 51.77% with a mean of 2.88%; 0.37 to 320.84% with mean value of 75.63%; and 0.39 to 33.40% with mean of 2.6%, in Omo Lante, Lante, Abulo, Ganta Kanchama and Zeyise Elgo sites respectively (Table 4.1). The CV of soil ESP values for the studied area was >100%, indicating strong variability among the samples. However, the numerical CV (107.59) value of the Ganta Kanchama site revealed nearly moderate variability of ESP.

The high variation might be due to the difference in parent material, topographic position, drainage, groundwater table, temperature, soil texture, land use type, degree of removal of basic cations by crop harvest, and management types. This is supported by the finding of Marcar (2016), who reported high water tables, insufficient soil permeability, inadequate drainage from irrigation systems, and topographic factors that cause an upslope recharge to cause a downslope salt outflow all leading to an accumulation of soil salinity. Fei et al. (2018) also found that land-use patterns, reclamation history, soil texture, and vegetation coverage were the most influential factors affecting spatial variation of soil salinity and sodicity.

Table 4. 1: Descriptive statistics for selected soil chemical properties around Abaya and Chamo Lakes

Sampling site	Dis. Sta	Soil Parameters								
		pH	EC (dS m ⁻¹)	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	Ca : Mg	SAR	ESP(%)
Omo Lante	N	39	39	39	39	39	39	39	39	39
	Min	7.30	0.38	0.40	0.08	17.43	5.73	0.37	0.07	0.30
	Max	8.57	6.13	78.45	11.46	51.72	47.69	7.33	13.75	19.21
	Mean	7.98	1.01	4.28	1.31	36.57	11.56	3.67	0.82	1.03
	Std. D	0.33	0.98	12.20	1.89	7.67	6.60	1.36	2.13	2.99
	CV%	4.14	96.62	285.11	144.85	20.98	57.11	37.07	258.80	289.47
Lante	N	44	44	44	44	44	44	44	44	44
	Min	8.04	0.34	0.07	0.08	11.23	4.44	0.68	0.02	0.73
	Max	9.64	4.68	75.72	16.78	47.37	40.94	4.63	17.84	25.31
	Mean	8.37	1.25	3.15	1.88	31.63	13.97	2.48	0.85	2.14
	Std. D	0.25	1.02	12.91	3.83	6.26	5.99	0.71	3.49	4.73
	CV%	2.94	81.81	409.26	203.73	19.78	42.89	28.65	411.34	220.58
Abulo	N	48	48	48	48	48	48	48	48	48
	Min	7.73	0.33	0.03	0.05	5.51	2.25	0.93	0.01	0.24
	Max	9.25	11.33	71.83	4.79	47.14	17.12	14.17	35.61	51.77
	Mean	8.33	1.69	5.26	0.85	29.25	9.46	4.33	1.88	2.88
	Std. D	0.26	2.22	13.01	0.92	10.70	4.84	3.52	5.82	8.31
	CV%	3.17	131.15	247.45	107.94	36.59	51.14	81.43	310.20	288.15
G/Kanchama	N	49	49	49	49	49	49	49	49	49
	Min	7.64	0.74	0.41	0.24	1.31	1.74	0.13	0.09	0.37
	Max	11.01	25.40	451.68	10.62	35.80	22.58	3.63	216.22	320.84
	Mean	8.82	4.22	158.96	2.78	19.92	12.13	1.67	51.24	75.63
	Std. D	0.92	4.93	144.99	2.28	9.16	4.19	0.71	54.97	81.37
	CV%	10.46	117.04	91.21	82.29	45.97	34.51	42.47	107.28	107.59
Zeyise Elgo	N	46	46	46	46	46	46	46	46	46
	Min	7.40	0.40	0.23	0.01	8.60	5.36	0.82	0.05	0.39
	Max	8.80	7.64	61.50	16.47	45.63	24.93	2.44	23.28	33.40
	Mean	8.16	1.43	6.18	1.23	28.44	16.27	1.80	1.63	2.60
	Std. D	0.28	1.44	11.93	2.39	6.41	4.60	0.33	3.88	5.28
	CV%	3.41	100.67	193.18	194.06	22.53	28.27	18.54	238.27	203.12

In the soils of Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites, the exchangeable Ca ranged from 17.43 to 51.72 cmol(+)/kg with a mean of 36.57 cmol(+)/kg; 11.23 to 47.37 cmol(+)/kg with a mean value of 31.63 cmol(+)/kg; 5.51 to 47.14 cmol(+)/kg with a mean of 29.25 cmol(+)/kg; 1.31 to 35.8 cmol(+)/kg with a mean of 19.92 cmol(+)/kg, and 8.6 to 45.63 cmol(+)/kg with a mean of 28.44 cmol(+)/kg, respectively (Table 4.1). According to the rating of Landon (2014), the exchangeable Ca in the soils of Omo Lante and Lante sites could be rated as high to very high; and that of Abulo and Zeise Elgo sites could be rated as medium to very high, respectively, while the

salt-affected soils in Ganta Kanchama site could be rated as very low to very high. The CV of soil exchangeable Ca for the studied salt-affected soils was between 10% and 100% for the studied salt-affected soils, which had moderate variability based on ratings of Terefe et al. (2021).

The exchangeable magnesium in the salt-affected soils of Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites, from 5.73 to 47.69 cmol(+)/kg with a mean of 11.56 cmol(+)/kg; 4.44 to 40.94 cmol(+)/kg with a mean value of 13.97 cmol(+)/kg; 2.25 to 17.12 cmol(+)/kg with a mean of 9.46 cmol(+)/kg; 1.74 to 22.58 cmol(+)/kg with a mean of 12.13 cmol(+)/kg; and 5.36 to 24.93 cmol(+)/kg with a mean of 16.27 cmol(+)/kg respectively (Table 4.1). According to Landon (2014) rating, exchangeable Ca in the soils of Omo Lante, Lante, and Zeyise Elgo sites could be rated as high to very high; and those of Abulo and Ganta Kanchama sites could be rated as rated medium to very high, respectively. The CV of soil exchangeable Mg had moderate variability based on ratings of Terefe et al. (2021) since its range falls CV between 10% and 100% for the studied salt-affected soils.

The Ca: Mg ratio is used to evaluate the potential impact of calcium on the uptake of Mg and P. As indicated in (Table 4.1), the Ca: Mg ratio of the soils in the study area varied from 0.37 to 7.33 with a mean of 3.67; 0.68 to 4.63 with a mean value of 2.48; 0.93 to 14.17 with a mean of 4.33; 0.13 to 3.65 with a mean of 1.67; and 0.82 to 2.44 with a mean of 1.8 in Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites respectively (Table 4.1). According to Landon (2014), when Ca: Mg ratios are less than 3:1, phosphorous (P) uptake may be inhibited, and it is suggested that the lowest acceptable limit with more subordinate Ca: Mg values, Ca availability slightly reduced. When the Ca: Mg ratio in the soil is less than 3, there is a higher magnesium concentration than calcium. This imbalance can affect calcium availability to plants because calcium and magnesium are positively charged ions (cations) and compete for uptake by plant roots (Gransee and Führs, 2013; Jing et al., 2024). When magnesium levels are high, it can outcompete calcium for absorption, leading to reduced calcium uptake by the plant (Lambers et al., 2019). Thus, the mean Ca: Mg ratio is less than 3:1 in the Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites where P uptake may be inhibited and calcium deficiency. In the Omo Lante site, the Ca: Mg ratio falls in the range of 3:1 to 4:1, which was the approximate optimum range for most crops, according to Landon (2014). The CV of Ca: Mg was moderate variability in the study area.

The exchangeable Na in the salt-affected soils of Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sites ranged from 0.40 to 78.45 cmol(+)/kg with a mean of 4.28 cmol(+)/kg; 0.07 to 75.72 cmol(+)/kg with a mean value of 3.15 cmol(+)/kg; 0.03 to 11.33 cmol(+)/kg with a mean of 5.26 cmol(+)/kg; 0.41 to 451 cmol(+)/kg with a mean of 158.96 cmol(+)/kg; and 0.23 to 61.50 cmol(+)/kg with a mean of 6.18 cmol(+)/kg, respectively (Table 4.1). According to Wogi et al. (2021) rating, exchangeable Na in the salt-affected soils of Omo Lante and Ganta Kanchama sites could be rated as medium to very high; and in those of Lante and Abulo sites could be rated as very low to very high, respectively, while that of Zeyise Elgo site could be rated as low to very high. The CV of soil exchangeable Na for the studied salt-affected soils had strong variability except for the Ganta Kanchama site, which had moderate variability based on the ratings of Terefe et al. (2021).

4.3.2 Geostatistical analysis and mapping of selected soil chemical properties

The spatial attribute is defined by the nugget/sill ratio or spatial dependence (SPD) $Co/(Co + C)$. When the value of $Co/(Co + C)$ is less than 0.25, the variable is said to have a strong spatial dependency; when it is between 0.25 and 0.75, it is considered to have a moderate geographic dependence; and when it exceeds 0.75, it is considered to have a weak spatial dependence (Addis et al., 2015; Nyengere et al., 2023; Sani et al., 2023; Yusuf et al., 2020). Table 4.2 shows the semivariogram obtained from the geostatistical study, illustrating the various geographical distribution models and levels of spatial dependency associated with the soil parameters. Semivariance revealed variations in the spatial dependence of soil parameters (Table 4.2). The nugget-to-sill ratio [$Co/(Co+C)$] of [pH, Mg, Na, SAR, and ESP] ranged from 0.25 to 0.75, as shown in Table 4.2, suggesting a moderate spatial dependence.

This implies that the properties were controlled by both intrinsic and extrinsic factors. It could be the continuous use of salt-affected irrigation water on the field, cultivation practices including plowing, fertilization, and other soil management practices (Lin et al., 2023; Sani et al., 2023; Shahinzadeh et al., 2022; Shi et al., 2021). This is in agreement with the findings of Jing et al. (2022) who reported that moderate spatial dependence is due to both intrinsic and extrinsic factors. According to Nyengere et al. (2023), the nugget/sill ratio ($C0/C0 + C$) <25% reflected a strong spatial dependence of [EC, Ca, and K]. The results of the distribution were explained by the model which shows to be affected by natural factors which are mostly geological in nature. This could be mainly due to the inherent/intrinsic sources of variability (e.g., natural variations in salt-affected soils, such as soil

texture, parent materials, and topography) (Yao et al., 2020). The majority of the researchers also stated that random extrinsic factors like soil management techniques like fertilization and plowing are related to weak spatial dependency, while strong spatial dependency is related to structural intrinsic factors like parent material, mineralogy, texture, climate, and topography. Conversely, a considerable degree of spatial dependence is probably influenced by both extrinsic and intrinsic variables (Abdu et al., 2023; Saleh, 2018; Ye et al., 2018). For soil EC, the nugget effect was typically higher (Table 4.2). This indicated that differences in soil qualities existed at short distances. The spatial variability at smaller distances than the lowest separation between measurements is associated with the nugget effect (Some'e et al., 2011; Yao et al., 2020).

The results indicated that the mean errors (ME) were near zero and the root mean square standardized error (RMSSE) was close to 1 for all studied soil parameters (Table 4.2). The result is similar to the finding of Abdu et al. (2023) who reported closer values of the mean error (ME) to 0, and closer values of the root mean square standardized error (RMSSE) to 1, suggesting that the prediction values were close to measured values, hence providing the most accurate predictions.

A wider range value means that different values of the soil property over longer distances have an impact on the observed values of this property (Takoutsing and Heuvelink, 2022; Yao et al., 2020). As indicated in Table 4.2, the spatial range values for all studied soil properties varied from 1344 m to 15,129 m, which is greater than the average sampling distance (200m), implying that the sampling interval in this study was sufficient to capture the spatial variability in studied soil properties. Thus, results indicate the sampling strategy was adequate. Similarly, Nogueira Martins et al. (2019) reported that if the range value is greater than the actual sampling distance, the sampling strategy is adequate to capture the spatial variability of studied soil properties.

Table 4. 2: Semivariogram models and model parameters for selected soil properties

Soil Property	Fitted Model	Nugget (Co)	Partial Sill (C)	Sill (Co + C)	Range (m)	SPD (Co/Co+C)*100	SPD Level	Estimated Error ME	RMSSE	
pH	Sph	0.754	0.350	1.104	2875.2	68.297	Mo	-0.002	0.84	
EC	Exp	0.256	1.023	1.279	9101	20.016	St	0.098	0.551	
Ex. Bases	Ca ²⁺	Exp	0.198	0.855	1.053	15129	18.834	St	-0.035	0.96
	Mg ²⁺	Sph	0.748	1.130	1.878	1344	39.830	Mo	-0.001	1.157
	Na ⁺	Sph	0.425	0.516	0.941	3106	45.207	Mo	0.027	0.045
	K ⁺	Gau	0.230	0.990	1.220	7824	18.852	St	0.044	0.956
SAR	Sph	0.369	0.553	0.922	3111	39.994	Mo	0.024	0.048	
ESP	Sph	0.388	0.441	0.829	4208	46.822	Mo	-0.169	1.181	

Where: Mo = Moderate, St = Strong, Sph = Spherical, Gau = Gaussian, Exp = Exponential

4.3.3 Spatial distribution map of selected soil chemical properties

4.3.3.1 Mapping the spatial distribution of soil pH

The area calculated from the interpolated map of salt-affected soil parameters created from measured point data is presented in Table 4.3, and its spatial distribution is shown in Figure 4.2. According to the rating of US Salinity Laboratory Staff (Richards et al., 1954), the interpolation result depicted that the study area is moderately alkaline to strongly alkaline (Table 4.3). The area calculated from the predicted map shows that 558.6 ha (99.8%), 232.8 ha (92.71%), 327.75 ha (75%), 375.25 ha (60%), and 427 ha (100%), of the salt-affected soils of Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeyise Elgo sampling sites respectively.

The soils of the studied area had pH values greater than 8.5 in Omo Lante, Abulo, and Ganta Kanchama; and between 7.5 and 8.5 in Lante and Zeyise Elgo sites (Table 4.3 and Figure 4.2). The soil pH could be rated as strongly alkaline in the Omo Lante, Abulo, and Ganta Kancham sampling sites and moderately alkaline in the Lante and Zeyise Elgo sampling sites, respectively, according to the ratings of the US Salinity Laboratory Staff (Richards, 1954) indicating a significant portion of the soils of the studied area requires alkalinity management practices. The soils of the studied area had a pH value greater than 7.5 (Table 4.3 and Figure 4.2) showing that alkaline salt-affected soils dominate the study area. This study highlighted a rise in alkalinity in the area compared to the earlier findings from EthioSIS (2016), which indicated neutral to moderate levels. Therefore, there is an urgent need for effective strategies to manage salinity and sodicity in the region. In the case of the Abaya and

Chamo Lakes region, the low rainfall and high evaporation rates are likely to be the primary factors contributing to the increased alkalinity of the salt-affected soils. The area is in a semi-arid climate, with an average annual rainfall of less than 600 mm. Moreover, the evaporation rate is very high due to the hot and dry environment (Bassa et al., 2023; Walche et al., 2023). These lead to the accumulation of salts in the soil, which can make it alkaline. The strongly alkalinity of the salt-affected soils may be attributed to low leaching of bases, especially in clay salt-affected soils (Landon, 2014; Mukungurutse et al., 2018).

The moderate to strong alkalinity might be due to the continuous irrigation practices with salt-affected irrigation water and shallow ground water table that happened in the study areas (Walche et al., 2023; Zewdu et al., 2017). This result is supported by the findings of Abdennour et al. (2021); Bortolini et al. (2018); and Sreedevi et al. (2019) which indicated alkalinity in arid and semi-arid areas is caused by irrigation water. The reason for this is that irrigation water can gradually introduce more salts into the soil and through evaporation the dissolved salts are concentrated in the soil solution (Allen and MacAdam, 2020; Minhas et al., 2020).

In addition, the alkalinity of the study salt-affected soils might have been resulted from the parent material, since they are in the Rift Valley, a region of volcanic activity, and the volcanic ash that has fallen over the area is often alkaline. Some fertilizers, such as lime and urea, can make the soil more alkaline, and some minerals, such as sodium bicarbonate and sodium carbonate, release alkaline ions when they dissolve in water (Moirana, 2023; Regassa et al., 2023; Van Straaten, 2002). The high alkalinity of the salt-affected soils around Abaya and Chamo Lakes can negatively impact agriculture. Alkalinity can reduce crop yields, make it difficult for plants to absorb nutrients, and increase disease risk (Bedadi et al., 2023; Zebire et al., 2019). Alkaline soils can lock up essential nutrients like iron, manganese, and phosphorus, making them less available to plants. This nutrient deficiency weakens the plant's health and makes it more susceptible to diseases (Das and Bhattacharya, 2017; Ghorbani et al., 2008).

4.3.3.2 Mapping the spatial distribution of soil electrical conductivity (EC)

Figure 1 shows the soil EC map generated by interpolating the point data result. There was substantial variation in soil electrical conductivity (EC) in various parts of the research area, as indicated by the area computed based on the projected map. About 558.01 ha (99.71%), 250.49 ha (99.36%), 420 ha

(96.11%), and 422.01 ha (98.93) of the studied salt-affected soils in Omo Lante, Lante, Abulo, and Zeyise Elgo sites respectively had EC values less than 4 dS m⁻¹ (Table 4.3). These salt-affected soils were generally categorized as free of excess salt, having no adverse effect on the growth and productivity of most crops according to the soil quality standards established by Landon, (2014; Wogi et al. (2021). However, the findings of this study showed some of the study areas have salt accumulation in the soils around Abaya and Cham Lakes. In contrast, the studies conducted by EthioSIS (2016), indicate that the soils around the study area were salt-free.

Table 4.3 shows that EC values for 339.82 ha (54.60%) of the Ganta Kanchama sampling site were between 4 and 8 dS/m. These values could be rated as slightly saline soil class throughout the studied area (Figure 4.2). One of the leading causes of soil salinization and sodicity in the area is the irrigation of agricultural land with subsurface and river water (which has a small amount of salt, but for the time being, it could develop gradually salt due to poor irrigation management) for more than 15 years. Salts may be brought to the soil's surface by irrigation water over time, where they can accumulate and harm crops. This is especially true in dry and semi-arid areas with little precipitation and considerable evaporation (Machado and Serralheiro, 2017; Tugwell-Wootton et al., 2020). It is encouraging that most of the studied agriculturally salt-affected soil area is non-saline and non-sodic. It implies that there is still time to take action to prevent further damage and that the problem still needs to be severe (Chhabra, 2022; Mohamed, 2017). According to the soil EC maps, it is incredibly reassuring to see that non-saline and slightly saline salt-affected soils are mainly concentrated throughout the entire study area (Al-Ali et al., 2021; Hailu and Mehari, 2021). It indicates that successful crop cultivation is still possible in various locations.

4.3.3.3 Mapping the spatial distribution of soil ESP

The distribution pattern of ESP values is shown in Figure 4.2. The distribution of ESP values shows a substantial difference in the study area. The spatial interpolation result indicated a considerable variation in soil ESP across different parts of the study area (Figure 4.2). The spatial interpolation result suggested that the area is dominated by soil sodicity of low to high risk rated according to Landon (2014). In terms of risks, 553.86 ha (98.97%), 232.94 ha (92.77%), 419.36 ha (95.96%), and 420 ha (98.36%) of the soils in Omo Lante, Lante, Abulo and Zeise Elgo sampling sites are classified under low (ESP < 5%) risks of sodicity, respectively (Table 4.3 and Figure 4.2). Under the low-risk level of ESP (<5%) sampling sites there could be medium to high soil exchangeable calcium amounts.

A high sodicity problem area with ESP (>15%) was observed in the Ganta Kanchama sampling site of the study area (Table 4.3 and Figure 4.2) which could be due to the higher exchangeable sodium found in the soil of these sampling site (Figure 4.3). These may result from the relatively high clay content of salt-affected soils in this study area site. The higher ESP results in this area are most likely due to the relatively high clay content of the salt-affected soils in the Ganta Kanchama sampling site (Walche et al., 2023). In sodic soils with high clay content, sodium ions can easily replace other cations (like calcium and magnesium) on the exchange sites. This leads to increased ESP and worsened sodicity (Choudhary and Kharche, 2018). Therefore, the high clay content in the Ganta Kanchama sampling site contributes to the higher ESP and sodicity problem. Because clay particles have a large surface area, there are more sites for sodium ions to bind to them. Furthermore, in sodic salt-affected soils, certain clay minerals, including smectite, are especially prone to dispersion (Bergaya et al., 2011; Javaheri et al., 2022). Smaller clay particles that are released into the soil have the potential to clog soil pores. This decreased water and air uptake may impede plant growth in the soil (Hailu and Mehari, 2021). Additionally, plants may find getting nutrients from sodic salt-affected soils the challenge being due to their high sodium level (Gangwar et al., 2020).

It is very encouraging that the study area is dominated by low to high-risk soil sodicity. This means that the area dominated by low risk soil sodicity is generally suitable for crop production (Aredehey et al., 2018; Tomaz et al., 2020). However, there is a need to manage and follow up on the status of the soil properties to ensure that the area remains favorable for crop growth. Here are some specific things that can be done to manage and follow up on the status of soil properties in the study area: monitor soil sodicity levels, maintain soil organic matter levels, use quality irrigation water that is low in sodium, and manage irrigation practices carefully. It is also important to select crops that are tolerant to soil sodicity (Mohammad et al., 2018; Mohanavelu et al., 2021; Stavi et al., 2021; Zaman et al., 2018).

Table 4. 3: The areal extent of the different classes of selected soil chemical properties with respect to sampling sites

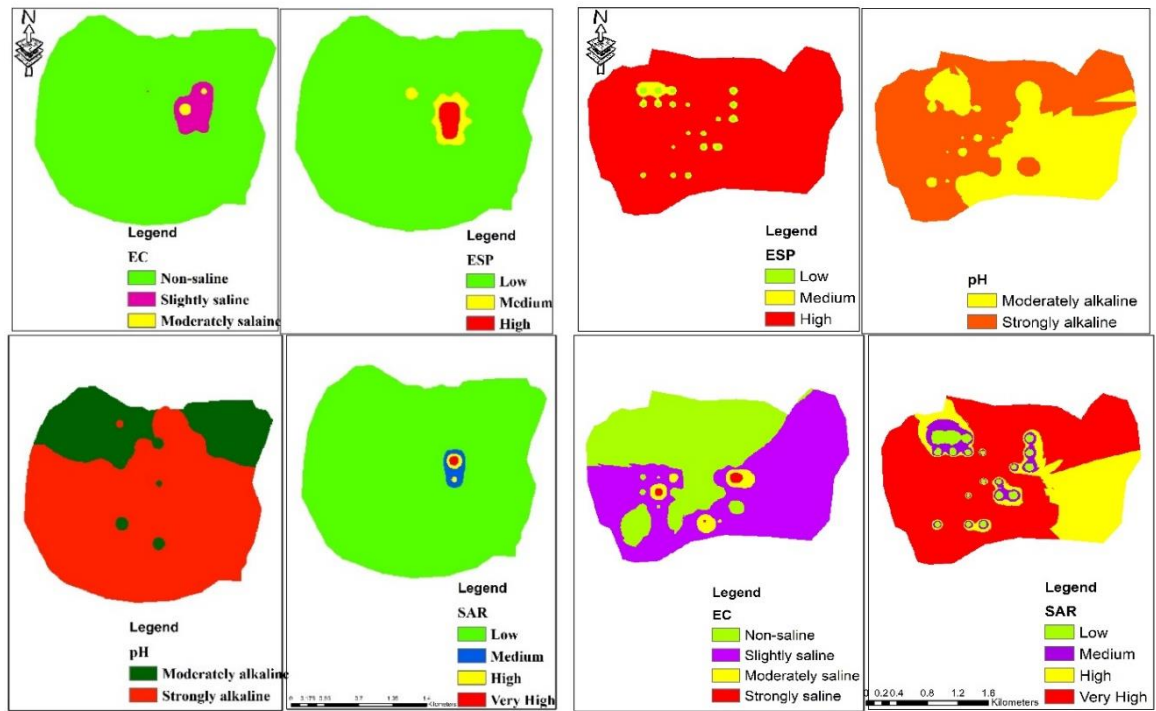
Soil properties	Rating	Status	Soil sampling sites									
			Omo Lante		Lante		Abulo		Ganta Kanchama		Zeyise Elgo	
			Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
EC (dS m ⁻¹)	<4	Non-Saline	558.01	99.71	250.49	99.36	420	96.11	263.46	42.35	422.01	98.83
	4-8	Slightly-Saline	1.64	0.29	0.6	0.24	16	3.66	339.82	54.62	5	1.17
	8-15	Moderately Saline	-----	-----	-----	-----	1	0.23	16.07	2.58	-----	-----
	>15	Strongly Saline	-----	-----	-----	-----	-----	-----	2.78	0.45	-----	-----
ESP (%)	<5	Low	553.86	98.97	232.94	92.77	419.36	95.96	4.59	0.74	420	98.36
	5-15	Medium	5.18	0.93	14.15	5.63	10.81	2.47	15.54	2.5	5.01	1.17
	>15	High	0.62	0.11	4	1.59	6.7	1.53	601.98	96.76	2	0.47
pH	7.5-8.5	Moderately alkaline	1.05	0.19	232.8	92.71	109.25	25.00	246.89	39.69	427	100
	>8.5	Strongly alkaline	558.6	99.81	18.29	7.29	327.75	75.00	375.23	60.32	0.1	0.02
Ex_Na	<0.10	Very Low	-----	-----	0.47	0.19	4.43	1.01	-----	-----	-----	-----
	0.1-0.3	Low	-----	-----	28.38	11.3	27.99	6.41	-----	-----	-----	-----
	0.3-0.7	Medium	0.03	0.01	146.38	58.3	18.98	4.34	-----	-----	0.3	0.07
	0.7-2.0	High	6.1	1.09	12.91	5.14	181.11	41.44	0.13	0.02	0.7	0.16
Ex_Ca	>2.0	Very High	553.56	98.9	62.94	25.07	204.37	46.77	621.99	99.99	426	99.76
	2-5	Low	-----	-----	-----	-----	-----	-----	1.32	0.21	-----	-----
	5-10	Medium	-----	-----	-----	-----	3.18	0.73	10.34	1.66	-----	-----
	10-20	High	0.33	0.06	1.57	0.63	23.19	5.31	177.58	28.55	0.01	0.02
Ex_K	>20	Very High	559.32	99.94	249.52	99.37	410.51	93.94	432.77	69.58	426.57	99.99
	<0.2	Very Low	0.38	0.07	1.01	0.4	7.72	1.77	-----	-----	0.5	0.12
	0.2-0.5	Low	9.86	1.76	57.47	22.89	101.1	23.14	0.32	0.05	0.5	0.12
	0.5-1.5	Optimum	504.06	90.05	185.41	73.85	301.08	68.9	38.24	6.15	152	35.6
Ex_Mg	1.5-2.3	High	30.16	5.39	7.17	2.86	26.92	6.16	153.9	24.74	230	53.86
	>2.3	Very High	15.3	2.73	-----	-----	-----	-----	429.7	69.07	44	10.3
	1.51-3.3	Medium	-----	-----	-----	-----	40.31	9.22	0.7	0.11	-----	-----
	3.31-8.3	High	15.69	2.8	1.08	0.43	92.23	21.1	11.68	1.88	0.07	0.02
	>8.31	Very High	543.96	97.2	250.02	99.58	304.3	69.63	609.73	98.01	426.53	99.98

Where: Units for the exchangeable bases (Na, Ca, K, and Mg) in cmolckg⁻¹



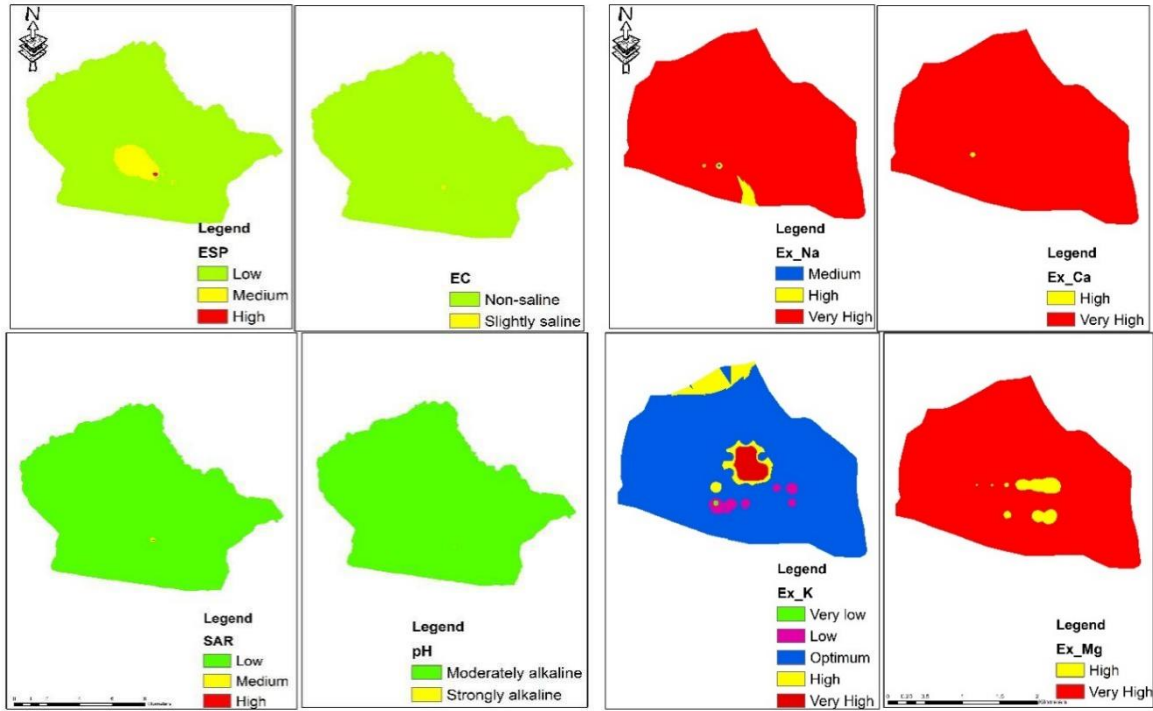
(A) Omo Lante

(B) Lante



(C) Abulo

(D) Ganta Kanchama



(E) Zeyise Elgo

(F) Omo Lante

Figure 4. 2: Spatial distribution map of pH, EC, ESP, SAR and Exchangeable bases of the salt-affected soils in the study area

4.3.3.4 Mapping the spatial distribution of exchangeable sodium

Figure 4.3 depicts the distribution pattern of exchangeable sodium values. There is a noticeable variation in the exchangeable sodium value distributions within the research area (Figure 4.3). As per Landon (2014), the spatial interpolation result (Figure 4.3) revealed that exchangeable sodium with a high rate dominates the area. It is evident that the soils of the research area significantly vary exchangeable sodium content, where most of them have very high levels of exchangeable sodium. This is probably caused by a number of factors, such as land use, soil type, and climate (Olorunfemi et al., 2018; Qadir and Schubert, 2002). There are several detrimental effects that high exchangeable sodium levels may have on soil health and plant growth. Waterlogging and root rot can result from exchangeable sodium's potential to decrease soil permeability and aeration (Huang, 2000; Syed et al., 2021) Additionally, it may more likely make nutrient loss and soil erosion. While limited leaching is generally a concern in such salt-affected soils, excessive irrigation can lead to leaching of nutrients, particularly nitrate, beyond the root zone (Wang and Li, 2019). To make sure

that the management strategies work, it's critical to periodically monitor the exchangeable Na level in the salt-affected soils (AbdelRahman, 2023; Rajendiran et al., 2015; Sivakumar, 2007).

4.3.3.5 Mapping the spaial distribution of exchangeable calcium

There was a slight variation in soil exchangeable calcium in different areas of the research region (Figure 4.3). The results of the investigation show that, overall, the soil exchangeable calcium in the study area is very high. The Ganta Kancham sampling site, on the other hand, was rated between low and very high in accordance with Landon (2014). According to Landon (2014); Wogi et al. (2021), the soils of Omo Lante, Lante, Abulo, Ganta Kanchama, and Zeise Elgo sampling sites have very high exchangeable calcium amounts (Figure 4.2, 4.3 and Table 4.3). Most of this study's findings were similar to those of the previous research EthioSIS (2016), which showed a high amount of calcium saturation, except for the Ganta Kancham sites. Also, it suggested detailed site-specific studies for the rest of the study areas.

The present findings suggest that the Ganta Kancham sampling site should be amended with calcium-rich materials, like gypsum and organic materials, to increase the availability of calcium, since according to Noori et al. (2021); Yadav et al. (2021), calcium is an essential nutrient for plant growth and development. However, the present findings also note that the exchangeable calcium amount is generally sufficient for crop production if the exchangeable sodium is managed regularly.

Exchangeable sodium is a harmful ion that can displace calcium from the soil exchange complex, making it unavailable to plants (Horneck et al., 2007; Meena et al., 2019; Ranjbar and Jalali, 2015). A high pH promotes the hydrolysis of sodium carbonate and bicarbonate, releasing sodium ions into the soil solution. This can further increase the exchange of sodium for calcium (Bui, 2017; Zewd and Siban, 2021). Therefore, it is essential to monitor the exchangeable sodium levels of the soils and apply appropriate management practices to reduce sodium levels that could be by leaching and application of gypsum. This will help ensure the soil has sufficient calcium for crop production (Kim et al., 2018; Watts and Dick, 2014; Zoca and Penn, 2017).

4.3.3.6 Mapping the spatial distribution of exchangeable magnesium

There was a variation in soil exchangeable magnesium in different areas of the research region (Figure 4.3). The findings of the study indicates that the soil exchangeable magnesium in the study area is generally very high, with the exception of the Abulo sampling site which was rated as medium to very high according to the rating of Landon (2014). The Omo Lante (Figure 4.2), Lante, Abulo, Ganta Kanchama, and Zeise Elgo sampling sites (Table 4.3 and Figure 4.3) have very high exchangeable magnesium amounts according to Landon, (2014); Wogi et al. (2021). The results are in line with those from EthioSIS (2016), which identified an optimal to a high level of magnesium.

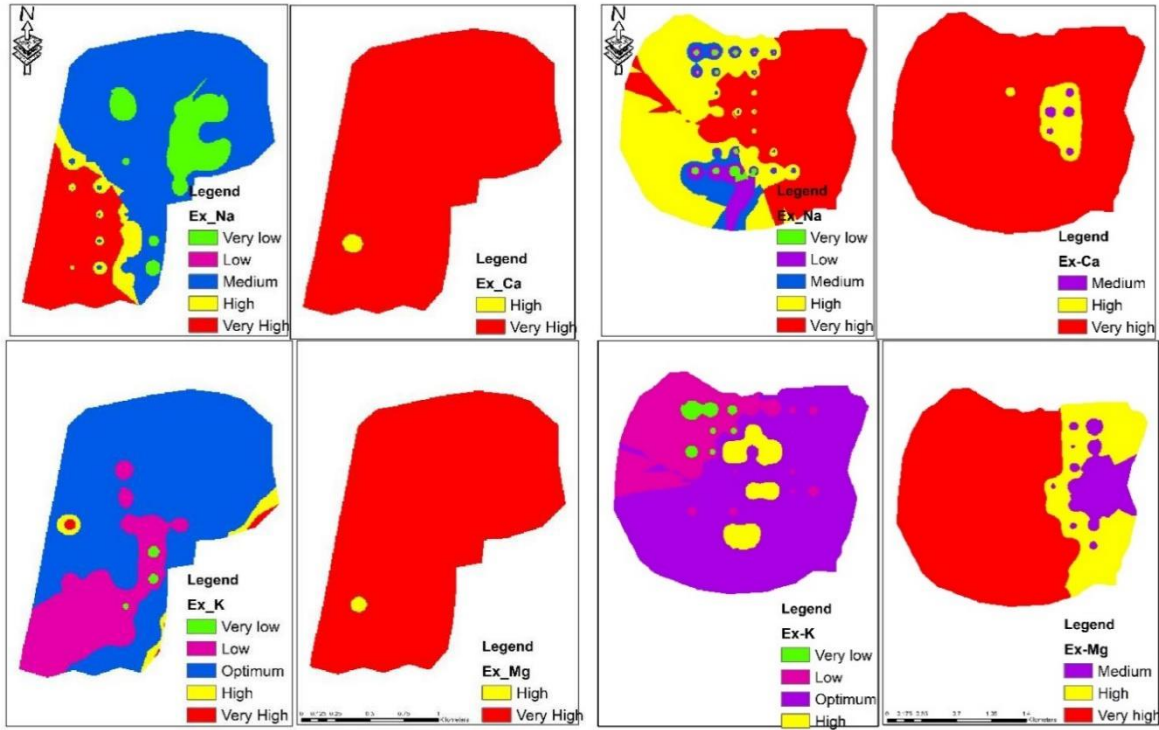
Basic cations like magnesium and calcium, are essential for plant growth (Bhatla et al., 2018; Rai et al., 2020). Their charges allow them to bind to negatively charged clay particles in the soil (Kumaragamage et al., 2021; Kumari and Mohan, 2021). The combination of high soil pH, limited rainfall, and parent material rich in calcium is probably what causes the raised calcium levels (Abbaslou et al., 2013). The similar trends in distributions, interpolations, and ratings of these nutrients suggest that similar factors control these nutrients, aiding farmers and land managers in better soil fertility and crop production (Panday et al., 2019; Tesfahunegn et al., 2011).

4.3.3.7 Mapping the spaiial distribution of exchangeable potassium

Figure 4.3 shows the soil exchangeable potassium map generated by interpolating the point data result. Variation in soil exchangeable potassium in various parts of the research area was indicated by the area computed based on the projected map. Generally, the exchangeable potassium values in the salt-affected soils of the study were rated in the range of optimum to very high according to Landon (2014); Wogi et al. (2021) (Table 4.3 and Figure 4.3). The results align with EthioSIS (2016), which found optimal to high potassium levels. The high soil exchangeable potassium in the study area could be attributed to the parent material of the salt-affected soils. The Rift Valley is a volcanically active location, and the fallen volcanic ash contains a lot of potassium (Balagizi et al., 2018) . Moreover, the Rift Valley's typically alkaline salt-affected soils help to better retain potassium (Alemayehu et al., 2016; Smith and Albert, 2023).

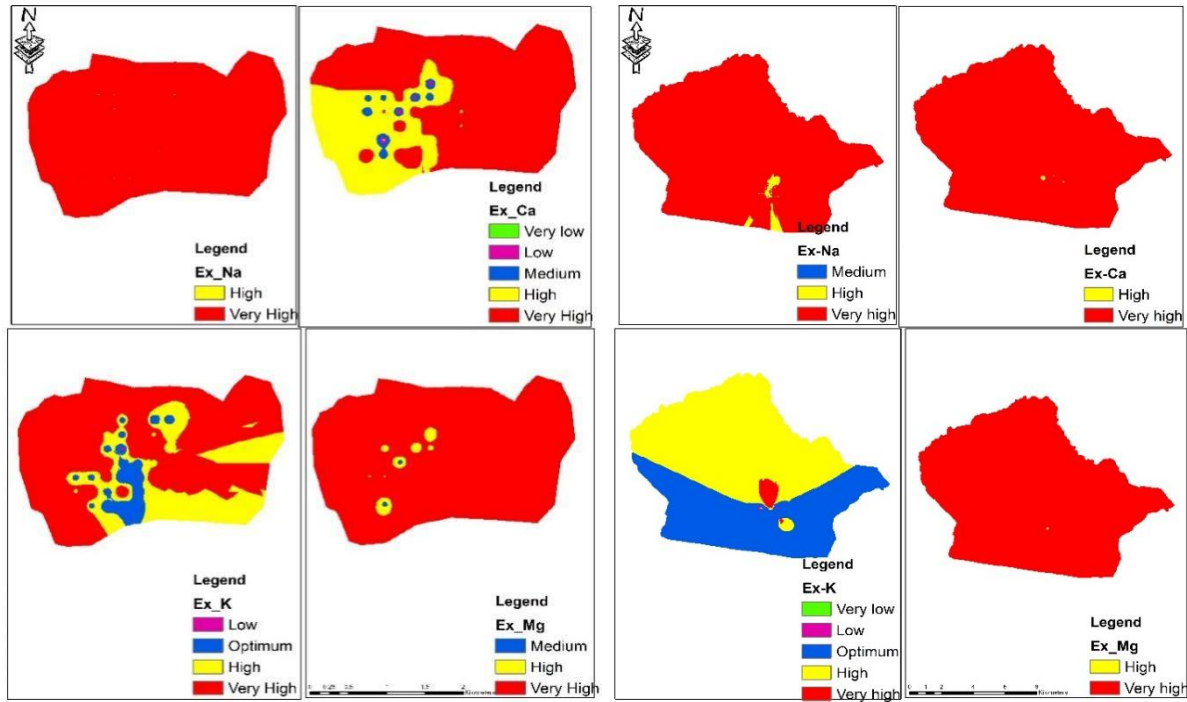
Potassium is required for photosynthesis, disease resistance, and fruit production. Among the crops that respond well to potassium are sweet potatoes, potatoes, and bananas (Dotaniya et al., 2016;

EL-Gioushy et al., 2022). The overall results of the study indicate that there is high potassium levels in the salt-affected soils of the Abaya and Chamo Lakes in the South Ethiopian Rift Valley which seem to make them generally suitable for crop growth (Walche et al., 2023; Zebire et al., 2019).



(G) Omo Lante

(H) Abulo



(I) Ganta Kanchama

(J) Zeyise Elgo

Figure 4. 3: Exchangeable bases spatial distribution map of the study area

4.3.4 Mapping the spatial distribution of salt affected areas

The distribution of salt-affected soils in the studied area showed spatially heterogeneous patterns throughout the studied area. According to the classification of salt-affected soils by Burt (2011), the salt-affected soils of the studied area are classified as neutral (non-saline non-sodic), saline, saline-sodic, and sodic (Table 4.4 and Figure 4.4). Among the sampling sites, the Ganta Kanchama site was found to be severely affected by sodicity (Table 4.4 and Figure 4.4), recording 602.96ha (97.54%).

The Ganta Kancham site had heavy clay soil texture, high temperature and shallow ground water table which can enhance the soil salinity and sodicity formation in the study area (Walche et al., 2023). Similarly, shallow groundwater depth has a higher influence on soil salinity rise, whereas a higher depth of groundwater level has a lower influence on soil salinization. A shallow ground water table leads to high capillary movement of water and increases the risk of salinization (Haj-Amor and Bouri, 2019; Zewdu et al., 2017). Due to capillary action, the salts in the soil are carried

by soil moisture and contribute to the production of salty and sodic soil when the water table is near the soil surface and the rate of evaporation is high (Gebremeskel et al., 2018; Kakeh et al., 2021). Thus, non-saline, non-sodic salt-affected soils take the most significant part of the total 2274.64 ha studied area (Table 4.4 and Figure 4.4).

4.3.5 Salt-affected soil type and distribution with respect to land form

As indicated in Figure 4.4, sodic and saline soil areas are laid on a relatively flat area in $<0-0.5\%$ in deep red and light red, respectively, according to FAO (2006) guidelines for soil descriptions. Saline salt-affected soils in the slope range of 1-2% and slope range 0.5-1% are indicated by orange and deep yellow color respectively (Figure 4.4). Most non-saline and non-sodic salt-affected soils were found in the slope $<2\%$ as showed in the figure 4.4 with different colors. The results indicate that almost all the salt-affected areas were situated in relatively lower slope positions exhibiting a flat to almost flat slope (0-2%), in accordance with FAO (2006) (Figure 4.4).

Salt-affected areas dominantly cover the flat terrain of the studied area around Abaya and Chamo Lakes, South Ethiopia Rift Valley (Bassa et al., 2023; Zebire et al., 2019). During the high rainy season, the runoff from the surrounding elevated and steep topography landform of Gamo highlands area flood the flat terrains around the Abaya and Chamo Lakes (Digga, 2023; Gindi, 2022). These areas are developed on almost flat to flat landforms (0-2%) and sometimes Sile, Elgo, Hare, Baso, and Kulfo Rivers overflowed and flooded the area during the high rainy season.

The results suggest that landform in the study area may influence the pattern and magnitude of spatial variability in salinity and sodicity of the soils in the study area. The lower elevation areas were very susceptible to soil salinization, whereas there is little influence, if any, by the process on the elevated areas (Corwin, 2021; Peng et al., 2019). Excessive evaporation and low-lying topography could be some of the factors responsible for the rising of soil salinity and sodicity at the lower elevations (Corwin and Yemoto, 2017). This is probably because if the land had high fine particles with poor drainage, it allows soluble salts within the irrigation waters to accumulate in the soil profiles and increase the salt concentration on the soil surface and then, as evaporation selectively removes the waters and leaves soluble salts on the soil (Moharana et al., 2019; Ortiz and Jin, 2021).

The present results are supported by the findings of Zewdu et al. (2017) which indicated low laying land form and area with shallow water table are greatly affected by salinity. Similarly low-lying topography and poor vegetation cover greatly enhanced the salinization (Zhang et al., 2021; Zhang et al., 2022). Zewdu et al. (2017) also confirmed that salt accumulation is more prevalent in low-lying landforms with relatively low elevations than in relatively steep landform areas.

Table 4. 4: Salt-affected soils type of salt class and areas concerning sampling sites.

Sampling Sites		Salt-affected soils type of salt class and area				
Omo Lante	Type of salt class	SSO	S	NSNSO	----	Total area
	Area(ha)	0.62	1.02	558.01	----	559.65
	Area (%)	0.11	0.18	99.71	----	100
Lante	Type of salt class	NSNSO	SO	S	SSO	Total area
	Area (ha)	0.02	0.01	0.01	228.77	228.81
	Area (%)	0.01	0	0	99.98	100
Abulo	Type of salt class	SO	S	NSNSO	SSO	Total area
	Area (ha)	0.2	10.78	419.41	6.5	436.9
	Area (%)	0.05	2.47	96	1.49	100
G/Kanchama	Type of salt class	S	SSO	SO	NSNSO	Total area
	Area (ha)	0.76	352.69	249.51	19.32	622.28
	Area (%)	0.12	56.68	40.1	3.11	100
Z/Elgo	Type of salt class	S	SSO	NSNSO	SO	Total area
	Area(ha)	1.59	4.99	420	0.43	427.01
	Area (%)	0.37	1.17	98.36	0.1	100

Where: S= Saline, SO = Sodic, SSO= Saline Sodic, NSNSO = Non-saline non-sodic

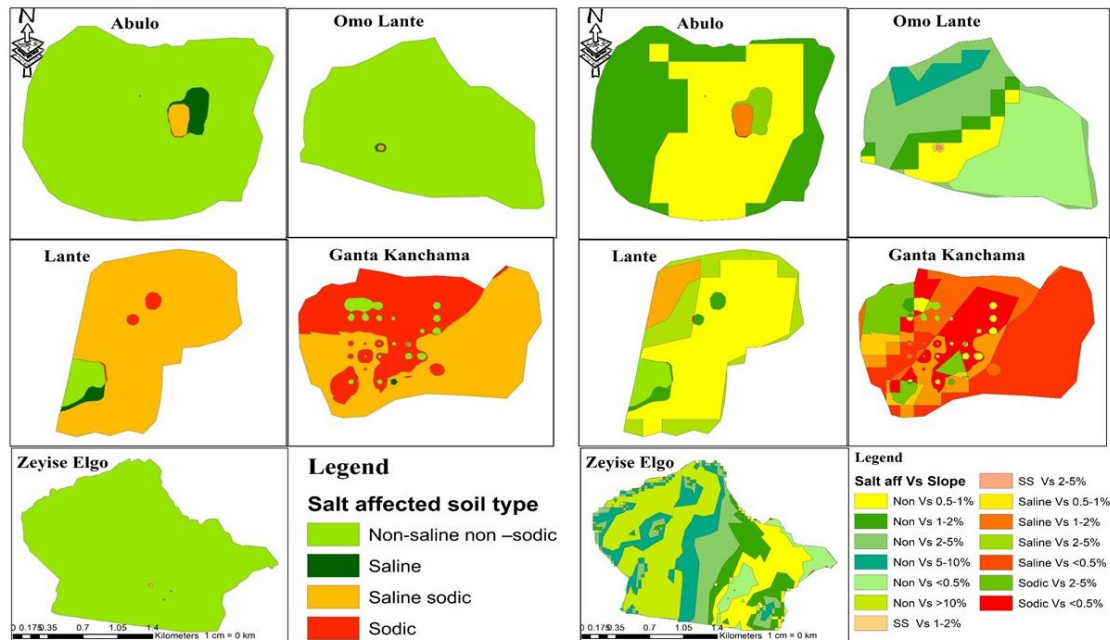


Figure 4. 4: Salt-affected soil type and distribution concerning land form (slope) of the study area

4.3.6 Recommended reclamation strategies of the studied agricultural salt-affected soils

It is important to note that the recommendations for soil remediation vary depending on the site's specific conditions, including the type and severity of salt-affectedness, the availability of water resources, and the cost of different remediation options (Batidzirai et al., 2012; Dhaouadi et al., 2020; Wicke et al., 2013). In general, leaching with irrigation water of high quality effectively removes salts from the soil. However, this can be expensive and time-consuming, especially in areas with limited water resources (Javadi et al., 2019; Mpela, 2021; Sultan and Ahmad, 2023). Amending with organic matter, such as compost or manure, chemical amendments (gypsum), and phytoremediation can also help improve soil structure and drainage, reducing salt accumulation. Leaching with good-quality irrigation water could be recommended for the Omo Lante, Abulo, and Zyise Elgo sites. In contrast, amendment with organic matter and chemicals (gypsum) and recommend leaching with good-quality irrigation water could be recommended for the Lante and Ganta Kanchama sites (Figure 4.5). Farmers should consult soil science experts for a specific remediation plan. Additional tips include drip irrigation, planting salt-tolerant crops, avoiding over-fertilization (Potassium chloride (KCl), Urea, Ammonium sulfate, Triple superphosphate (TSP), Monoammonium phosphate (MAP) and Diammonium phosphate (DAP) and monitoring soil salinity levels. The previous studies on soil fertility mapping suggested soil fertilizer recommendations. They addressed some of the current soil properties in the research location (EthioSIS, 2016), but did not conduct detailed soil salinity and sodicity investigations concerning the extent and distribution of salts. Hence, it is better to conduct salt-affected soil mapping at the country level.

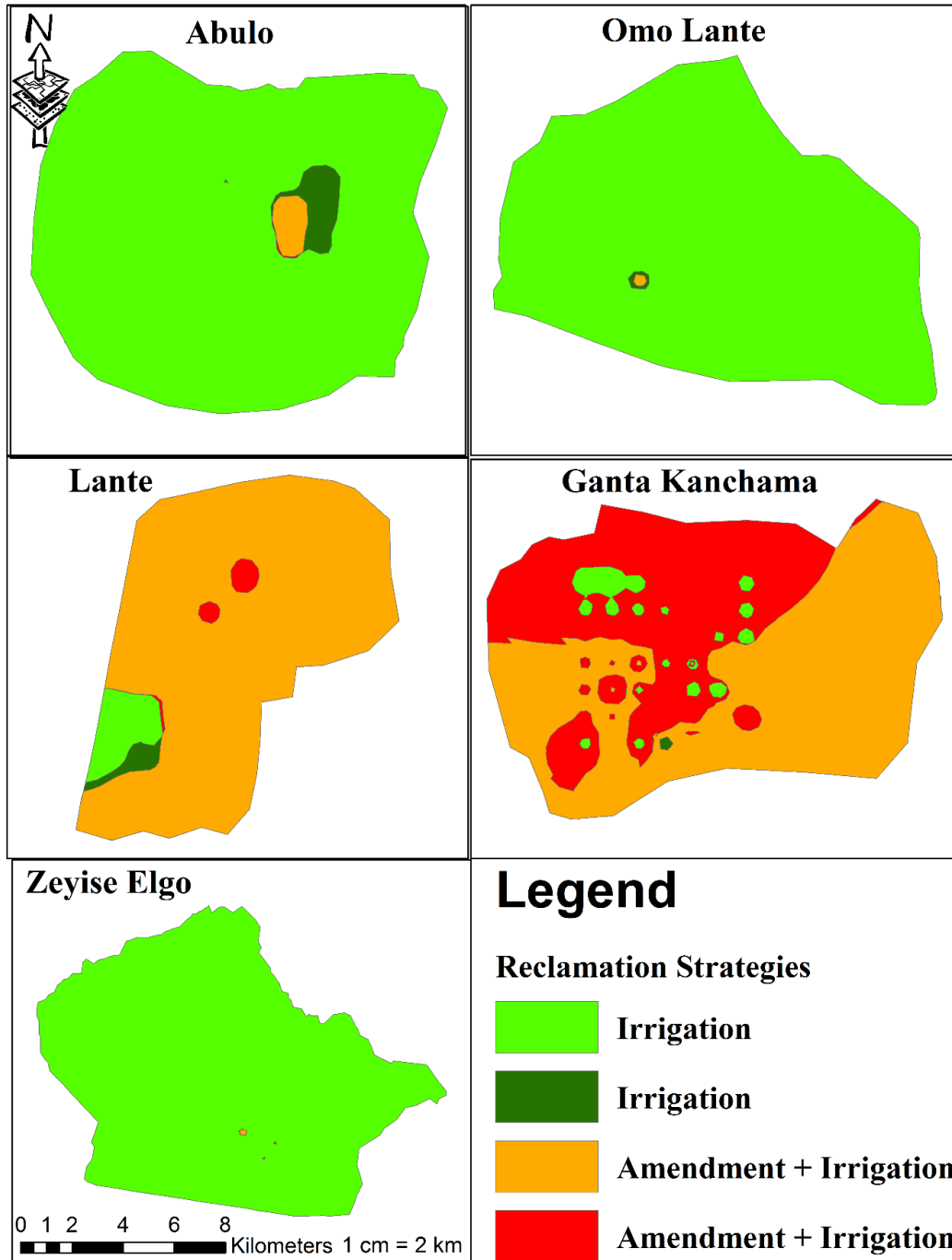


Figure 3.1: Map of recommended reclamation strategies of the studied agricultural salt-affected soils around Abaya and Chamo Lakes South Ethiopia Rift Valley (where IR = Irrigation water for leaching).

4.4 Conclusion

Soil sodication and salinization are recognized as the major land degradation mechanisms and agricultural productivity reduction. Alkaline soil reactions dominated the study area. Salt-affected soils were generally categorized as free of excess salt, having no adverse effect on the growth and productivity of most crops. The spatial interpolation result in exchangeable sodium percentage (ESP) however suggested that the area is dominated by low to high-risk soil sodicity and a noticeable variation in the exchangeable sodium value distributions within the research area. The current study reveals a wide range of spatial heterogeneity in terms of types and severity among different salt-affected soil classes, implying that site-specific reclamation measures are required to address the current salinity and sodicity problems of the soils of the study area. Previous studies on soil fertility mapping suggested fertilizer recommendations but did not investigate soil salinity and sodicity, indicating the need for detailed country-level salt-affected soil mapping.

The study area should be prevented from accumulation of excessive salts, monitored, and appropriate salt-affected soil reclamation measures be implemented to sustain soil productivity in the studied area. Generally, amendments with organic matter, such as compost or manure, chemical amendments (gypsum), and phytoremediation can also help improve soil structure and drainage, reducing salt accumulation. Leaching with good-quality irrigation water could be recommended for the Omo Lante, Abulo, and Zyise Elgo sites, whereas amendment with organic matter and chemicals (gypsum) could be recommended the Lante and Ganta Kanchama sites based on the findings of the present study. However, farmers should consult soil science experts for a specific reclamation plan.

4.5 References

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5. ELUCIDATING AMENDMENT RESOURCES FOR RECLAIMING EFFICACY OF SODIC SOILS AROUND ABAYA AND CHAMO LAKES, SOUTHERN ETHIOPIA RIFT VALLEY

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ABSTRACT

Sodic soils are harmful to agricultural and natural environments in Ethiopia's semi-arid and arid regions, leading to soil degradation and reduced productivity. This study investigated how amendment sources could help improve the chemical properties of sodic soils around the Abaya and Chamo Lakes in the South Ethiopian Rift Valley. A Completely Randomized Design (CRD) was used to set up a factorial experiment conducted to investigate the effects of gypsum (GYP) and farmyard manure (FYM) on sodic soil reclamation. A pot experiment consisting of a factorial combination of four levels of GYP (0, 50, 100, and 150%) and four levels of FYM (0, 10, 20, and 30 tons ha⁻¹), with three replications was used to conduct this specific study. The pots were incubated for three months and leached for one month, after which soil samples were collected and analyzed for selected soil chemical properties. Analysis of variance (ANOVA) was performed to determine the optimal amendment level for sodic soil reclamation. The results showed that applying 10 ton FYM ha⁻¹ and gypsum at 100% gypsum requirement (GR) rate resulted in a 99.8% decrease in exchangeable sodium percentages (ESP) compared to untreated composite sample and a 1.31% reduction over the control (GYP 0% + FYM 0 ton ha⁻¹). The treatments led to a decrease in soil electrical conductivity, exchangeable sodium (Ex. Na), and ESP values. The results were confirmed by the LSD test at 0.05. It is fascinating to see how different treatments have such a significant impact on soil properties. The prediction models indicate that ESP's sodic soil treatment effect ($R^2 = 0.95$) determines the optimal amendment level for displacing ex. Na from the exchange site. The best estimator models for ESP using sodic soil treatment levels were $ESP = 1.65 - 0.33 \text{ GYP}$ for sole gypsum application and $ESP = 1.65 - 0.33 \text{ GYP} + 0.28 \text{ FYM}$ for combined GYP and FYM application, respectively. The study found that combined GYP and FYM applications reduced ESP to less than 10% in agricultural soil, but further research is needed to determine their effectiveness at the field level.

Keywords: sodic soil; soil properties; semi-arid region; gypsum; farmyard manure; principal components analysis

5.1 Introduction

A balanced nutrient application is necessary for long-term agricultural production and soil health since plant nutrients are essential to crop productivity (Shahane and Shivay, 2021). Nutrient availability in the soil is influenced by the physico-chemical characteristics of the soil and management factors (Karami et al., 2012). Since salt ions are more prevalent in alkaline soil, crop growth is limited by the availability of nutrients (Dotaniya et al., 2023). The higher cation concentrations such as sodium (Na), calcium (Ca), and magnesium (Mg), along with the associated anions like chloride (Cl), sulfates (SO₄), carbonate (CO₃), and bicarbonate (HCO₃) restrict the availability of critical plant nutrients (Abbas et al., 2022). Sodic soils are a severe problem, particularly in dry and semi-arid areas (Tashayo et al., 2020).

Exchangeable sodium percentages (ESP) of > 15, an electric conductivity (EC) of more than 4 dS m⁻¹, and a saturation extract sodium adsorption ratio (SAR) lower limit of 13 are all characteristics of sodic soils. Therefore, the fundamental problem in these soils is Na⁺ (Chhabra, 2004). In sodic soils with high sodium concentrations and low EC_e cause dispersion of soil aggregates. When the electrolyte concentration drops below the flocculation value of the clay, it leads to clay dispersion (Marchuk, 2013). Low levels of salt are present in sodium-affected soils, which also have weak structural stability, low hydraulic conductivities, and low infiltration rates (Levy and Sumner, 2020). Due to poor aeration and insufficient water availability, crop production is low due to these bad physical characteristics. Significant soil erosion might also result from low infiltration rates (Hailu and Mehari, 2021).

Soils containing high concentrations of sodium ions or soluble salts are known as soils. Interestingly, it was estimated that the initial global distribution of these soils covered around 1 billion hectares in the late 1970s. However, the global distribution has since undergone sporadic adjustments (FAO, 2020). Saline and sodic soils significantly impact global food security, leading to stunted growth and lower yields (Kumar and Sharma, 2020). Salinization and sodification make previously productive land unusable for agriculture, decreasing global food production (Hossain et al., 2020). By 2050, up to 50% of arable land could be affected by salinity. Coastal areas are

particularly vulnerable, and climate change-induced sea levels exacerbate salinization (Muniruzzaman, 2012). Globally, nearly 2000 ha of agricultural land is loss of production every day because of salinization (Zaman et al., 2018).

In Ethiopia, it was reported that there are over 11 million hectares of unproductive, naturally soils, ranking the country as first in Africa, followed by Kenya (8.2 million hectares), Nigeria (5.6 million hectares), and Sudan (4.8 million hectares) (Bellido-Jiménez et al., 2021; Habtamu and Wassie, 2022). The dry and semi-arid agro-ecologies, which constitute about half of Ethiopia's land area, are considered challenging for crop development due to the high salinity level in the soil and water (Asad et al., 2018). Arid and semi-arid regions in the country have been soils affected by salt, particularly sodic ones (Dagar, 2013). The impact of saline-sodic and sodic soils on crop production in the irrigated lands of Ethiopia's arid and semi-arid regions is severe. The presence of sodic soil due to the expansion of irrigated agriculture seriously threatens the sustainability of crop yields in the area (Hailu and Mehari, 2021).

The pH of sodic soils ranges from 8.5 to 10. The hydrolysis of Na_2CO_3 is what causes the high pH. Chloride, SO_4 , and HCO_3 are the three major anions in the soil solution of sodic soils, with smaller amounts of CO_3^{2-} . Ca^{2+} and Mg^{2+} precipitate because of the high pH and the presence of CO_3^{2-} , which results in a low soil solution of Ca^{2+} and Mg^{2+} (Al-Busaidi and Cookson, 2003). In addition to Na^+ , K^+ is another soluble and exchangeable cation that may be present in these soils (Gondek et al., 2020). Techniques like drip irrigation, precision agriculture, choice of salt-tolerant crops, and application of gypsum can help manage these problems (Paz et al., 2023). A multi-pronged approach involving climate change, innovative technologies, and sustainable land management practices is needed to address these challenges (Bayabil et al., 2021; Gupta et al., 2020).

According to Chaganti and Crohn, (2015), traditional sodic soil restoration often entails applying and incorporating gypsum into the soil as well as applying extra water for leaching. It is crucial for water to pass through and into the soil. It dissolves the gypsum, makes it easier for calcium to travel to the exchange sites, and replace sodium that was once exchangeable (Choudhary, 2017). This, in addition to applying gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or CaCl_2 to remove the exchangeable Na^+ from the exchange sites, can be an effective way to improve soil quality and promote better plant

growth (Bello et al., 2021). In the exchange of Ca^{2+} and Na^+ ions, Na^+ leaches out as a soluble salt, like Na_2SO_4 or NaCl . In addition, CaSO_4 and CaCl_2 can also increase permeability by increasing the electrolyte concentration (Choudhary and Kharche, 2018). Extensive research has been undertaken on the properties of sodic soils and their amelioration, with a focus on the physical aspect (Gangwar et al., 2020; Kripal, 2016).

While using chemical amendments to remove sodium from the soil's cation exchange sites which is required to reclaim sodic soils, leaching is the most efficient way to remove soluble salts from the rhizosphere in salty soils (Choudhary and Kharche, 2018; Kudakwashe et al., 2022; Srivastava et al., 2019). Saline-sodic soils can be made productive to yield a good crop through proper management practices (Li and Kang, 2020). In this regard, finding the most effective reclamation technique or combination of technologies to enhance crop yields and manage farmland in saline-sodic soil is essential (Kudakwashe et al., 2022). Gypsum is a commonly used amendment material due to its availability and affordability (Levy and Sumner, 2020). According to Prapagar et al. (2012), combining farm yard manure (FYM) and gypsum (GYP) can effectively restore sodic soils. Apparently, this process works by increasing the level of Ca^{2+} ions while reducing the amount of Na^+ ions on the exchange sites. In turn, the excess Na^+ is removed from the root zone or via leaching water out of the soil profile (Öztürk et al., 2023).

Calcium accumulation on the exchange sites can contribute to better soil aggregation in sodic soil, which in turn can help reduce the soil's bulk density (Rowley et al., 2021). Calcium is typically obtained from the amendments that have either soluble Ca^{2+} or can dissolve Ca^{2+} upon reacting with soil (Argüello et al., 2022). Gypsum and organic matter have recently been used for soil reclamation (Bello et al., 2021). Gypsum, FYM, and PM can impact soil pH, Na concentration, and the availability of nutrients like N and S to plants. It is good to know that this information is used to manage alkaline soils (Dotaniya et al., 2023). The incorporation of rice husk can significantly impact the soil's electrical conductivity (EC), pH, and sodium adsorption ratio (SAR) by decreasing these parameters (Wijitkosum, 2020). According to a field trial, cow manure was found to improve the physical properties of soil, while rice husk increased the number of soil pores (Pratiwi and Shinogi, 2016).

Organic matter has several benefits for soil. It can enhance soil structure and aggregation, improve hydraulic conductivity, and increase nutrient levels and cation exchange (Hafeez et al., 2022; Minhas et al., 2019). Adding a combination of organic and inorganic materials to soil can help speed up the process of SOM mineralization. These can, in turn, improve the concentration of plant nutrients in a soil solution. It is also interesting that saline-sodic soils typically require higher organic matter levels to increase production (Dotaniya et al., 2023). FYM and gypsum can complement each other in several ways, especially by improving soil health (Dotaniya et al., 2023).

According to research, FYM provides organic matter and helps calcium ions move into the soil more easily (Powlson et al., 2013). This is particularly important for sodic soils, where gypsum alone can slowly remove sodium. However, when FYM is added, the process is accelerated as it improves soil structure and allows for better movement of calcium ions and sodium displacement (Bello et al., 2021; Yash et al., 2022). Combining FYM and gypsum can provide a synergistic approach to soil reclamation and sustainable agricultural practices. The long-term effects of FYM on soil structure and nutrient availability also extends the benefits of gypsum application. It can reduce the need for frequent additions of gypsum and ensure sustained soil improvement, which is beneficial for sustainable farming (Rathi et al., 2020; Walche et al., 2023).

It is crucial to have site-specific information on soil management to ensure the best possible product for farmers. Investigating sound land management practices for the reclamation of sodic soils around Abaya and Chamo Lakes in Southern Ethiopian Rift Valley is essential, especially when considering the long history of agriculture in that region. Finding sustainable solutions is critical to enable farmers to continue their livelihoods while preserving the environment for future generations. This will ensure that site-specific management advice based on site-specific data that can be provided to effectively utilize the limited land resources.

A thorough soil examination is necessary to ensure the practices are utilized to their full potential. Using farmyard manure and gypsum together to restore soil quality sounds like an exciting approach that could have positive results. To that end, this experiment was designed to successfully improve the soils in the study area. The research was conducted to replace sodium and lower the exchangeable sodium percentages (ESP) of sodium-affected soil to a level that is suitable for agriculture. In general, the rearrangement lies in combining the individual strengths of

gypsum and farmyard manure to achieve a more effective and sustainable approach to reclaiming sodic soils. The study utilized multivariate analysis to select the optimal treatment model for reclaiming sodic soil through application of gypsum and farmyard manure. It was aimed at determining and comparing the appropriate levels of reclaiming materials required for the process.

5.2 Materials and Methods

5.2.1 Soil sampling and sample preparation

Collecting bulk soil samples involved using a nursery auger and spades to randomly collect surface soil samples (0–20 cm depth) to be reclaimed from the identified sodicity problem area of Ganta Kancha site around Abaya and Chamo Lakes by Walche et al. (2023). After collection, the soil samples were taken to the lab and spread on a polythene sheet for air-drying. The soil samples were carefully combined and sieved through a 5 mm sieve to reduce heterogeneity. The laboratory procedures outlined by US Salinity Laboratory Staff were followed during the analysis (US, 1954). The initial soil sample was analyzed for pH, EC, exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , and Na^+), CEC, ESP, and SAR (Table 5.1). A pH meter with a combined glass electrode in water (H_2O) was used to measure the pH of the soil at 1:2.5 soil to water ratio, in accordance with Rayment and Lyons (2011) recommendations.

Saturated soil paste extracts were used to measure electrical conductivity using a conductivity meter, as described by (Miller and Curtin, 2006). A pH 7.0 solution of 1 M ammonium acetate (NH_4OAc) was used to extract the exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) from the soil (Jackson, 1967). Exchangeable Ca^{2+} and Mg^{2+} were determined in the leachate using an atomic absorption spectrophotometer, but exchangeable K^+ and Na^+ were determined via flame photometry (Rowell, 1994). From the NH_4^+ saturated samples, which were then replaced by K^+ using a KCl solution, the soil's potential cation exchange capacity (CEC) was determined. K^+ displaced ammonium, which was quantified using the micro-Kjeldahl technique, and the excess salt was removed by washing with ethanol (Chapman, 1965) and reported as CEC. The sodium adsorption ratio (SAR) was calculated by the procedure outlined in Hand Book No. 60 (Richards, 1954). ESP values were calculated as the percentages of the exchangeable Na to the soil's CEC.

5.2.2 Laboratory analysis of irrigation water

The initial irrigation water was analyzed as per Table 5.1. The analysis of the physio-chemical parameters of the water samples was carried out using standard laboratory procedures. The pH (H₂O) and EC_w were determined with the help of a pH meter and an electrical conductivity meter, respectively. A flame photometer was used to determine soluble Na⁺ and K⁺ (Alemu and Desta, 2017), while soluble Ca⁺² and Mg⁺² were analyzed directly by an atomic absorption spectrophotometer (Arain et al., 2008). Using a technique of Zamanpoore et al. (2019), the argentometric method was used to measure chloride (Cl⁻), calcium carbonate (CaCO₃), and bicarbonate (HCO₃⁻) by a process that involves titrating against a silver nitrate standard solution with potassium chromate indicator, while spectrophotometric analysis was used to determine the levels of phosphate (PO₄⁻³), nitrate (NO₃⁻), nitrite (NO₂⁻), and sulphate (SO₄²⁻) (Horwitz, 1975). The sodium adsorption ratio (SAR) was estimated using Equation 1, as recommended by Richards (1954). The ion concentrations in this relationship are given in milligrams per liter or milliequivalents per liter.

$$SAR = \frac{Na \text{ meq/L}}{\sqrt{(Ca + Mg)/2}} \quad (1)$$

Equation 2 was used to estimate the residual sodium carbonate (RSC) in irrigation water, as recommended by Raghunath (1987), to see its impact on the soil's salt content. The concentrations of each ion in this relationship are given in milliequivalents per liter.

$$RSC = (CO_3 + HCO_3) - (Ca + Mg) \quad (2)$$

Table 5. 1: Selected properties of the untreated composite sodic soil (0–20 cm depth) and irrigation water

<u>Soil</u>			<u>Irrigation Water</u>		
Parameter	Units	Value	Parameter	Units	Value
Texture	---	Heavy Clay	pH	-----	8.3
Clay	%	64	EC _w	dS m ⁻¹	1.184
Silt	%	30	Na ⁺	mg L ⁻¹	17.96
Sand	%	6	K ⁺	mg L ⁻¹	3.90
Bulk Density	g cm ⁻³	1.4	Ca ²⁺	mg L ⁻¹	26.20
Gypsum Requirement	tons ha ⁻¹	10	Mg ²⁺	mg L ⁻¹	13.56
Farmyard Manure	tons ha ⁻¹	20	Cl ⁻	meq L ⁻¹	0.45
pH	-----	10.6	CO ₃ ⁻²	meq L ⁻¹	Nil
EC	dSm ⁻¹	3.5	HCO ₃ ⁻	meq L ⁻¹	2.46
Ex. Na	cmol(+) kg ⁻¹	48	PO ₄ ⁻³	meq L ⁻¹	Nil
Ex. K	cmol(+) kg ⁻¹	1.16	NO ₃ ⁻	meq L ⁻¹	1
Ex. Ca	cmol(+) kg ⁻¹	3.19	NO ₂ ⁻	meq L ⁻¹	1
Ex. Mg	cmol(+) kg ⁻¹	2.18	SO ₄ ²⁻	meq L ⁻¹	0.46
CEC	cmol(+) kg ⁻¹	52.1	Salinity	% (ppt)	0.59
ESP	%	95	SAR	----	1.04
SAR	---	37.1	RSC	meq L ⁻¹	0.02

Where EC_w = electrical conductivity of water; Ex = exchangeable; SAR = sodium adsorption ratio; ESP = exchangeable sodium percentage; RSC = residual sodium carbonate; ppt = parts per trillion

5.2.3 Amendments preparation and application

Decomposed farmyard manure (FYM) was selected as the organic amendment for this experiment. The chemical composition of FYM was determined at Horticoop Ethiopia (Horticulture) PLC, Soil, Water, and Plant Analysis Laboratory in Debera Zeit, Ethiopia. The chemical compositions determined were pH = 8.26, EC = 7.81mS/cm, Ca²⁺ = 43698.50ppm, Mg²⁺ = 11544.50ppm, K⁺ = 2121.30ppm, OC = 10.9%, and TN = 1.01%. pH was determined based on ES ISO 10390:2014 (1:2:5) and EC based on ES ISO 11265: 2014(1:5) mentioned under section 1.4. Ca, Mg, and K were determined by Strong Acid Digestion + ICP OES determination (Margu et al., 2005). OC was determined based on Walkely and Balck's methods mentioned under section 1.4. TN was determined based on ES ISO 11261: 2015 (Kjeldahl Method), mentioned under section 1.4. The organic amendment was ground to pass through a 2 mm sieve to ensure uniformity. The soil samples were mixed and crushed for the pot experiment to achieve a uniform dry bulk density of 1.4 g cm⁻³ (Wogi et al., 2021). It is significant to note that due to variations in soil packing and

other reasons, the bulk density of each pot can vary (Håkansson and Lipiec, 2000). The procedures used for the study were as stated by Heluf (1995). The process outlined involved using agricultural grade gypsum (GYP) powder of 98% purity that was sieved through a 2 mm sieve to ensure uniformity and high solubility. This was then mixed with farmyard manure in the pots at a depth of 20 cm. According to the USSLS (1954), the amounts of added gypsum were determined to reduce ESP to 10%, which is acceptable (US, 1954). We used the methods established by Zia et al. (2006) to determine the appropriate amount of gypsum needed to replace exchangeable sodium to achieve the desired level of sodicity (Equation 3) for a given unit of land area with sodic soils (Appendix Figure 5.2).

$$GR = CEC * d * BD * 0.81(ESPi - ESPf)/f \quad (3)$$

Where BD = bulk density of soil (1.4 g cm^{-3}), GR = required amount of GYP in (10 t ha^{-1}), CEC = cation exchange capacity in (52.1 cmol (+)/kg) of soil, d = depth (0.2 m) of soil to be reclaimed and soil structure has to be improved, $ESPi$ = actual (95%) ESP of the soil as determined by analysis, $ESPf$ = final ESP to be ascertained after reclamation (10%), and f = purity of gypsum applied (98%)

5.2.4 Experimental design, treatments and laboratory analysis

Combining gypsum (GYP) and farmyard manure (FYM) for reclamation of sodic soil is not based on a single, specific protocol. It draws upon several scientific principles (GYP) and findings from various studies (FYM) with different methodologies (Osman, 2018)). Accordingly, the GYP levels were calculated from the gypsum requirement principal formula (2.4, Equation 3), and FYM levels drew upon the recommendations of various studies (Bekele et al., 2019; Hailu and Mehari, 2020; Singh et al., 2019; Yaduvanshi, 2017).

A Completely Randomized Design (CRD) was used to set up a factorial experiment with four levels of GYP 0% (0 ton ha^{-1}), 50% (5 ton ha^{-1}), 100% (10 ton ha^{-1}), and 150% (15 ton ha^{-1}) and four levels of FYM ($0, 10, 20, \text{ and } 30 \text{ tons ha}^{-1}$), with three replications (Appendix Figure 5.1:). The number of treatments was 16, with three replicates making 48 plastic pots/plot/. The plastic pot used in this experiment had a perforated bottom with drainage outlets, a 19.2 cm bottom diameter, a 23 cm top diameter, a 19.5 cm depth (height), and a 6833.5 cm^3 capacity. A wider top

diameter of plastic pot can allow better drainage and aeration, and excess water can drain out more readily (Bunt, 2012). In addition, the plastic pot had more holes, and holes positioned strategically can help ensure drainage and prevent waterlogging, even with constricted flow lines (Maguire and Woods, 2017).

Five kilogram of air-dried soil samples that through 5 mm sieve was placed in each pot with a factorial combination of the treatments. All pots were incubated in a shade house for 90 days (3 months) and wetted regularly to maintain FC as per US Salinity Laboratory Staff (1954) (Richards et al., 1954). After a period of 90 days of incubation, the soil in each plastic pot was leached for 28 days, which is equivalent to one month. To determine the pore volume of water prior to the leaching process, the soil in the plastic pots was saturated with a specific amount of water from the bottom of the pot until water appeared on the top of the soil (Alemayehu et al., 2017). The determined 2.5 L of water was applied to each pot, considering evaporation loss of 5% under ideal conditions with low wind, clay, or organic-rich soil, large pots, and slow and deep irrigation (Lamb et al., 2014). The application was completed through 4 irrigation cycles per treatment with seven (7) day intervals. In total, 10 L of water was applied to each pot uniformly through 4 rounds. Irrigation water from the Kulfo River, was used for leaching. At the end of the incubation and leaching period, soil samples were collected from every pot using a soil corer to collect a cylindrical soil sample from the entire pot depth, dried, and analyzed for chemical properties.

The pH, EC and exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) were determined as mentioned under section 5.2.2. Despite these challenges, a somewhat empirical approach has been used to successfully relate the relative and total concentrations of soluble cations in the saturation extract of soils to the exchangeable-cation composition (Richards, 1954). Hence, the ESP formula was developed from the empirical approach used for this study.

$$SAR = \frac{Na^+}{\left(\frac{Ca^{2+} + Mg^{2+}}{2}\right)^{\frac{1}{2}}} \quad (4)$$

$$ESP = (100(-0.0126 + 0.01475(SAR))/1) + (-0.0126 + 0.01475(SAR)) \quad (5)$$

5.2.5 Data Analysis

Prior to the analysis of variance (ANOVA), the assumption of normality was checked using the Shapiro–Wilk normality test, and two-way ANOVA was used to elucidate the appropriate and best amendment level to reclaim the sodic soil. The LSD test was used to measure the mean separation between treatments and determine the significance at 0.05 SAS, Ver. 9.4 (Barbudo et al., 2012).

The model used for sodic soil amendments (GYP + FYM) was as follows:-

$$Y_{ij} = \mu + A_i + B_j + AB_{ij} + e_{ij}$$

where Y_{ij} = the soil properties on soil treatments of i th GYP and j th FYM;

μ : overall mean;

A_i : the effect of i th % (GYP: 0, 50, 100, and 150);

B_j : the effect of j th *ton/ha* (FYM: 0, 10, 20 and 30);

AB_{ij} : interaction of the effect of i th GYP and j th FYM;

e_{ij} : error.

Multivariate analyses (PROC COR, PROC REG, PCA, cluster) were carried out to differentiate appropriate or optimum treatment and to develop a best treatment level model to reclaim sodic soil using soil chemical properties with high correlation coefficient (CV %) of treatments with output of soil variables. The impacts of treatments were determined with coefficient of determination (R^2), $C(p)$ statistic, and SE (standard error) across the soil amendments (GYP and FYM). The multiple linear regression models used for fitting uniform soil chemical properties for fixed effects were as follows: $A = \pi r^2$

$$Y_j = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_n X_n + e_j$$

where Y_j = dependent variable (soil chemical properties/ESP) $A = \pi r^2$;

α = intercept;

$X_1, X_2, X_3 \dots X_n$ = the amendment level (GYP + FYM) used to reclaim sodic soil;

$\beta_1, \beta_2, \beta_3 \dots \beta_n$ = regression coefficient of the independent variables $X_1, X_2, X_3 \dots X_n$;

e_j = residual error.

5.3 Results and Discussion

5.3.1 Initial soil and irrigation water quality

A preliminary study was conducted to analyze the physicochemical properties of the experimental soil and irrigation water quality before the incubation and leaching experiment. The soil was found to be heavy clay with a pH of 10.6 and an EC of 3.5 d Sm^{-1} (Table 5.1). The Exchangeable Sodium Percentage (ESP) was also determined to be 95%, indicating that the soil can be categorized as sodic in the Ganta Kanchama site (FAO, 2020). According to (Alka et al., 2012), the availability of most nutrients, pH, and ESP solubility could all be significantly impacted. The irrigation water used for leaching was suitable and safe according to Richards (1954) (Table 5.1).

5.3.2 Effects of gypsum and farmyard manure on chemical properties of sodic soil after incubation and leaching

5.3.2.1 Soil pH and electrical conductivity

The study showed that the pH of the soil was not substantially ($p > 0.05$) changed by the single or combined application of FYM and gypsum compared to the control. However, increasing application of gypsum alone decreased the initial pH of the soil, which is quite important for the availability of plant nutrients. Nevertheless, continuous decreases in soil pH could have unintended consequences by undesirably affecting plant nutrient availability, and altering the chemical composition of the soil (Osman and Osman, 2013). Hence, it must be followed up with soil pH and maintained (Table 5.2). This might be the result of applying more gypsum, which would have increased the pace at which the Ca^{2+} and Na^+ exchange reactions occurred when the concentration of Ca^{2+} rose due to the gypsum dissolving (Amer, 2015).

Combined application of gypsum and FYM had significant effects ($p < 0.05$) on soil EC over the control and other treatments. The highest EC values recorded for the combined applications of gypsum and FYM at gyp0 + 0fym, gyp50 + fym0, and gyp150 + fym0 resulting EC values of

11.84, 11.83, and 11.97 d Sm⁻¹, respectively. However, the lowest EC values were recorded for gyp0 + fym30, gyp150 + fym20, and gyp150 + fym150, respectively (Table 5.3). All the treatments increased the EC values of the samples over control but increased combined application of gypsum and FYM decreased EC as observed by FYM over the control (Table 5.3), which would require further leaching. This might be because adding gypsum to a soil alters the chemistry of the soil by increasing the quantity of salt that is dissolved, which prevents the clay component from expanding and dispersing (Keren, 2023).

Generally, the study revealed an increase in soil electrical conductivity due to adding gypsum and FYM to sodic soils at the initial hydrolysis stage, indicating potential salt accumulation (Louis, 2015). While the treatments are beneficial for reducing sodicity, high electrical conductivity can hinder plant water and nutrient absorption and must be balanced through critical soil EC testing and control (Husson, 2023). According to Amer (2015), both FYM and gypsum are helpful because they help the process by supplying organic acids that break down native calcium carbonate (CaCO₃) and release additional Ca²⁺ for replacement. Gypsum provides Ca²⁺ to replace Na⁺. Replacing exchangeable Na⁺ ions with Ca²⁺ or H⁺ enhances water infiltration and soil aggregation.

As FYM levels rise, GYP and other salts dissolve in the soil solution, replacing Na⁺ at the soil exchange site. This could explain the notable decrease in EC with rising FYM levels. This aligned with the findings of Eshete (2022), which reported that applying both organic and inorganic ameliorants together was a better way to lower the EC of the soil than applying the treatments alone. Increased soil porosity and hydraulic conductivity from the simultaneous application of FYM and gypsum at varying rates reduced EC, which enhanced the leaching of dissolved salts (Adane et al., 2019; Challa et al., 2022; Eshete, 2022).

The increased H⁺ of the soil solution as a result of FYM addition dissolved gypsum and other salts to replace Na⁺ in the soil exchange site which might be the cause of the decrease in EC with combined treatments. This was in agreement with Osman and Osman, (2018), who reported that in order to lower the E_c of soil, a combined application of organic and inorganic ameliorants was preferable compared to the sole application of treatments e.

In general, combined addition of gypsum and FYM, allowing them incubate for three months, and then leaching them for one month improved the chemical reaction and enhanced the soil exchange

site to replace Na^+ by Ca^{2+} . Similarly, the FYM-caused removal of excess ions by enhancing the physical characteristics of the soil, which might be the cause of the decrease in EC values (Khan et al., 2022). The present findings are also supported by the results of other authors who reported decline in EC values as a result of combined application of gypsum and FYM at varying rates (e.g., Argüello et al., 2022; Page et al., 2021)

5.3.2.2 Soil exchangeable basic cations (Na^+ , Mg^{2+} , Ca^{2+} , and K^+)

The sole GYP and FYM levels had a significant ($p < 0.05$) effect on the exchangeable Ca^{+2} and K^+ contents (Table 5.2). In contrast, the combined application of gypsum and FYM level and their interactions had highly significant ($p < 0.05$) effects on exchangeable Na^+ and Mg^{+2} (Table 5.3). The data in Table 5.3 demonstrate that the application of treatments at different levels resulted in a significant release of exchangeable Na due to a chemical reaction between the cations in the chemical amendments and the Na in the soil exchange site.

It is possible to infer a trend from figure 5.1 and table 5.3 that the concentration of Ca^{2+} increased with the increasing rate of combined application of GYP and FYM, whereas sole application of FYM had a non-significant effect ($p < 0.05$) while sole application of gypsum had significant effect, and the highest exchangeable calcium ($11.69 \text{ cmol (+) kg}^{-1}$) was obtained at the application of 150% GYP level. The Ca was consumed in higher amounts, replacing more Na from the exchange site (Table 5.3 and Figure 5.1). However, when treatments were applied in combination, exchangeable Na levels were significantly ($p < 0.05$) lower (Table 5.3). Thus, combined application of gyp150% with 30 t FYM and 20 t FYM ha^{-1} rates reduced exchangeable Na by 2.75% and 2.832.65% over the control, respectively.

The application of 10 t FYM ha^{-1} and 100% GR rate of gypsum, followed by 0 t FYM ha^{-1} and 100% GR rate, resulted in a relatively maximum reduction of exch. Na, 95.8% and 3.05%, over the control, respectively (Figure 5.1). The decrease in exchangeable Na from 4.12 to 2.77 cmol (+) kg^{-1} in this study is likely due to the change in concentration of Ca^{2+} from 7.15 to 11.69 cmol (+) kg^{-1} (Table 5.3). This is because Ca^{2+} and Na^+ compete for exchange sites on the soil colloid (Tertre et al., 2011). When the concentration of Ca^{2+} in the soil solution is increased, more Ca^{+2} will be adsorbed onto the exchange sites, displacing Na^+ (Minkina et al., 2014). This approach is beneficial as Na^+ can have an adverse impact on the soil's properties and crop growth (Gondek et

al., 2020; Hafez et al., 2021). High levels of exchangeable Na can lead to soil dispersion, reducing water infiltration and aeration. Exchangeable Na can also be toxic to plants, especially at high concentrations (Brar et al., 2015; Khoshnevisan et al., 2021). The study results suggest that increased Ca^{2+} concentration effectively decreases exchangeable Na in the soil (Singht et al., 2021). This can have several positive benefits for soil health and crop production (Ampong et al., 2022).

The combined application of gypsum and farmyard manure (fym) has a synergistic effect on exchangeable Mg, indicating that the effect of the combined application is greater than the sum of the individual effects (Table 5.3). This is likely due to several factors, including gypsum displacing exchangeable Na from the soil colloids that allows more Mg to be adsorbed. FYM improves the soil structure and increases the cation exchange capacity (CEC) of the soil, which provides more binding sites for Mg (Bouajila et al., 2023). Moreover, this increase in CEC, Mg, Ca, and K contents may benefit plant growth and production. However, excessive levels of CEC could lead to plant nutritional imbalances and must be appropriately managed. Farmyard manure (FYM) also contains Mg, which contributes to the increase in exchangeable Mg (Fekadu et al., 2018).

Results revealed that exchangeable Mg was increased from 4.29 to 10.1 $\text{cmolc}\cdot\text{kg}^{-1}$. The highest exchangeable Mg was recorded at the combined application of gypsum 50% + 30 t FYM ha^{-1} rate (Table 5.3). This rate of gypsum is likely sufficient to displace a significant amount of exchangeable Na from the soil colloid (Zhang et al., 2021). At the same time, the FYM provides additional Mg and improves the soil structure and CEC (Brar et al., 2015).

Sole application of gypsum increases the amount of calcium in the soil from 7.15 to 11.69 $\text{cmol} (+) \text{kg}^{-1}$ (Table 5.2). This could be because gypsum is a calcium sulfate mineral, and when it dissolves in water, it releases calcium ions (Ca^{2+}) into the soil solution. These calcium ions can then be adsorbed onto the soil colloid, increasing the amount of exchangeable calcium in the soil (Argüello et al., 2022; Zhang et al., 2021). Sole application of farmyard manure (FYM) had a significant effect ($p < 0.05$) on potassium (K) in sodic soil by improving soil structure and increasing cation exchange capacity (Table 5.2). FYM contains K, making it more available to plants (Aytenew and Bore, 2020). The amount of K in FYM varies depending on the manure source and management practices (Singht et al., 2021).

5.3.2.3 Soil exchangeable sodium percentage (ESP)

Combining treatments of 10 t FYM ha⁻¹ and gypsum at 100% GR rate, followed by 0 t FYM ha⁻¹ and gypsum at 100% GR rate, resulted in a maximum (99.8%) drop and a 1.31% decrease in ESP values over the control, respectively (Table 5.3 and Figure 5.1). According to Haque et al. (2015); and Sundhari et al. (2018), sodic soil reclamation benefits from the combined application of FYM and GYP. The ESP value was reduced to levels below the allowable limit (ESP < 10%) by the combined application of FYM and gypsum (Table 5.3 and Figure 5.1). However, it is crucial to note that even low ESP levels can pose problems, particularly in agricultural soils. Maintaining ESP within safe limits is essential for soil health and crop productivity (Osman, 2018).

The control treatment also decreased the ESP to values less than the permissible limit (Table 5.3). This could be because the control treatment had a 3-month incubation period and a 1-month leaching time. This created an opportunity for natural sodic soil reclamation by dissolving native calcium carbonate and making calcium available in the solution, thereby reducing exchangeable sodium (Table 5.3). Dissolving calcium cations through amendment and leaching decreases the soil relative Na⁺ concentration in the water, lowering the exchange complex's sodicity levels (Chhabra and Chhabra, 2021; Singht et al., 2021). The sulfur in the gypsum will oxidize in the damp soil with the help of soil microbes to generate sulfuric acid, which will dissolve the lime (calcium carbonate) and release its calcium into the solution to replace the sodium on the soil exchange sites (Bui, 2017; Reemtsma et al., 1999).

The maximal amount of Ca²⁺ that can be dissolved in the incubated and leaching-treated sodic soil with combined application of gypsum and farmyard manure stays dissolved once applied to the soil (Kitila et al., 2020). The optimal solution for the reclamation problem will be determined using 10 t FYM ha⁻¹ and gypsum at 100% GR rate quantity as a strong control limitation. After a specific calcium amelioration method, the soil solution's relative Na⁺ concentration reduced to roughly 47% while the electrolyte content increased, bringing the sodicity in the exchange complex to ESP = 10 (Charlet and Tournassat, 2005).

Processes related to salinity and sodicity occur over significantly longer periods, from weeks to months. We assume the exchange mechanism is at a local thermodynamic equilibrium since determining the sodium cation in the soil solution and the sodium cation in the exchange complex

(Opfergelt et al., 2014) requires the application of the well-known Gapon equation (Mau and Porporato, 2016). This was in agreement with the study of Ranjbar and Jalali (2015), which showed a significant amount of exchangeable Na was released because of the chemical substitution between the cations in the treatments and the Na⁺ in the soil exchange site. The explanation for this could be that gypsum provides soluble Ca²⁺ directly to replace exchangeable Na. At the same time, FYM uses chemical and biological processes to convert the comparatively insoluble carbonates of Ca and Mg that are frequently found in soils into soluble forms that can replace Na⁺ (Geng et al., 2022; McKenzie et al., 2004).

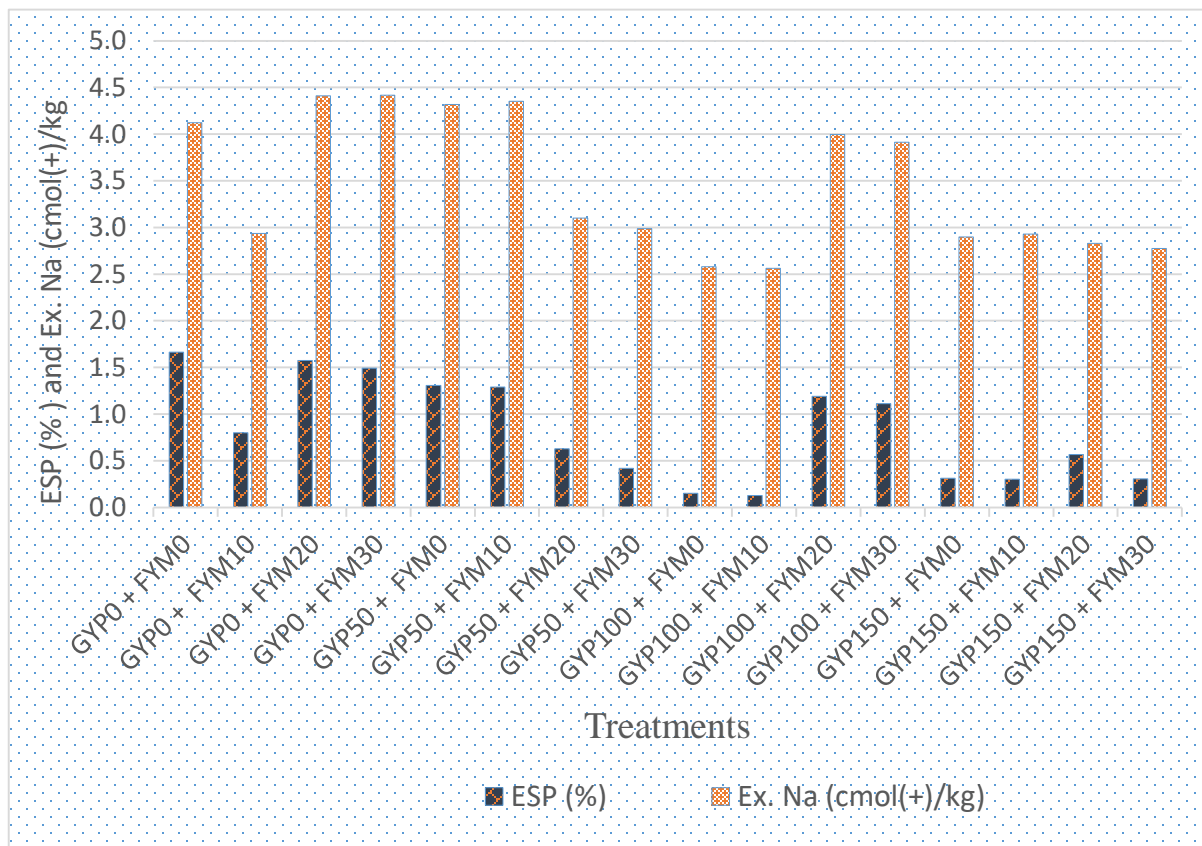


Figure 5. 1: Effect of gypsum (GYP) and farmyard manure (FYM) treatments on exchangeable sodium percentages (ESP) and exchangeable sodium (Ex. Na) of sodic soil under incubation and leaching study.

Where GYP 0% would represent no gypsum application (0 tons/hectare, control), GYP 50% would apply half the required amount (5 tons/hectare), GYP 100% would mean using the complete calculated requirement (10 tons/hectare), GYP 150% would apply 50% more than the calculated

requirement (15 tons/hectare), FYM 0 tons/hectare would represent no FYM application (control), FYM 10 tons/hectare would apply half the required amount, FYM 20 tons/hectare would mean using the complete calculated requirement, and FYM 30 tons/hectare would apply 50% more than the calculated requirement.

Table 5. 2: Main effects of gypsum and farmyard manure on sodic soil chemical properties

Treatments	GYP (%)			Treatments	FYM t ha ⁻¹		
	pH	Ex. Ca	Ex. K		pH	Ex. Ca	Ex. K
0	9.86	7.15 ^c	0.6	0	9.86	9.59	0.52 ^b
50	9.81	8.79 ^b	0.6	10	9.77	9.79	0.68 ^a
100	9.86	10.64 ^a	0.55	20	9.78	8.96	0.52 ^b
150	9.65	11.69 ^a	0.53	30	9.77	9.94	0.56 ^b
LSD (0.05)	ns	1.31	ns	LSD (0.05)	ns	ns	0.09
CV%	2.6	24	23	CV%	2.7	30	20

Means within a column followed by the same letters are not significantly different at 0.05 levels.

Table 5. 3: Combined application of gypsum and farmyard manure interaction effects on sodic soil chemical properties

GYP (%)	FYM (t ha ⁻¹)	EC	Ex. Na	Ex. Mg	SAR	ESP
0	0	11.84 ^{ab}	4.12 ^{ab}	4.29 ^{cd}	1.81 ^a	1.66 ^a
	10	11.32 ^{abc}	2.94 ^{cde}	4.13 ^{cd}	1.28 ^{bcdef}	0.80 ^{bcdef}
	20	11.24 ^{abc}	4.41 ^a	8.15 ^{ab}	1.75 ^{ab}	1.57 ^{ab}
	30	9.33 ^d	4.42 ^a	7.72 ^{ab}	1.70 ^{ab}	1.49 ^{ab}
50	0	11.83 ^a	4.32 ^a	6.73 ^b	1.59 ^{abc}	1.31 ^{abc}
	10	11.09 ^{ab}	4.35 ^a	7.88 ^{ab}	1.58 ^{abc}	1.29 ^{abc}
	20	11.12 ^{abc}	3.10 ^{bcde}	7.24 ^b	1.17 ^{cdef}	0.63 ^{cdef}
	30	10.18 ^{bcd}	2.99 ^{cd}	10.11 ^a	1.04 ^{def}	0.42 ^{def}
100	0	11.14 ^{abc}	2.58 ^e	6.84 ^b	0.87 ^f	0.15 ^f
	10	10.79 ^{abcd}	2.56 ^e	7.99 ^{ab}	0.86 ^f	0.13 ^f
	20	10.84 ^{abcd}	4.00 ^{abc}	3.85 ^d	1.52 ^{abcd}	1.19 ^{abcd}
	30	11.99 ^a	3.91 ^{abcd}	6.12 ^{bc}	1.47 ^{abcde}	1.11 ^{abcde}
150	0	11.97 ^a	2.90 ^d	8.10 ^{ab}	0.97 ^{ef}	0.31 ^{ef}
	10	10.97 ^{abc}	2.93 ^{cde}	7.96 ^{ab}	0.97 ^{ef}	0.30 ^{ef}
	20	10.05 ^{cd}	2.83 ^{de}	3.42 ^d	1.14 ^{cdef}	0.57 ^{cdef}
	30	10.25 ^{bcd}	2.77 ^e	3.48 ^d	0.97 ^{ef}	0.31 ^{ef}
LSD (0.05)		1.42	0.97	2.18	0.46	0.74
CV (%)		7.26	16.91	20	21.16	53.75

Means within a column followed by the same letters are not significantly different at $P \leq 0.05$ levels.

5.3.3 Soil color change

The change of soil color from dark black to brown after gypsum and farmyard manure application to salt-affected sodic soils can be attributed to several factors (Chhabra and Chhabra, 2021). These include the displacement of sodium by calcium, oxidation of organic matter, chemical reactions with iron, and leaching of salts (Bui, 2017; Roy and Chowdhury, 2021). GYP (CaSO_4) introduces Ca^{2+} ions into the soil and the Ca^{2+} ions replace Na^+ ions adsorbed onto clay particles, a process called cation exchange. Na^+ dominance disrupts soil structure and contributes to the dark black color. Replacing Na^+ with Ca^{2+} improves soil aggregation and drainage, leading to a lighter brown color (Gaur et al., 2022; Robin et al., 2015; Yan et al., 2024).

Under sodic conditions, organic matter accumulates and remains un-decomposed, contributing to the dark color. The improved drainage and aeration facilitated by GYP and FYM application can stimulate microbial activity, leading to faster decomposition of organic matter (Chhabra and Chhabra, 2021; Hebbar et al., 2023). This decomposition releases CO_2 and dark humic substances, resulting in a lighter brown color. Sodic soils often have reduced Fe, contributing to the dark color. Adding GYP can lead to oxidation of Fe from Fe (II) to Fe (III) oxides. These Fe (III) oxides have reddish-brown hues, which can blend with the remaining organic matter to create a browner color (Jalali and Ranjbar, 2009; Singht et al., 2021). GYP, FYM, and improved drainage can facilitate the leaching of soluble salts from the soil depth (profile). These salts can mask the true color of the soil by appearing as a white crust on the surface. The underlying brown color becomes more prominent as the salts are leached away (Figure 5.2) (Litalien and Zeeb, 2020; Mohiuddin et al., 2022). Reclaimed sodic soil has improved oxygen access to plant roots, loosens up, and lowered pH value, resulting in a brown color (Stavi et al., 2021). This indicates soil health improvement and a shift from dark black to brown (Das et al., 2022).

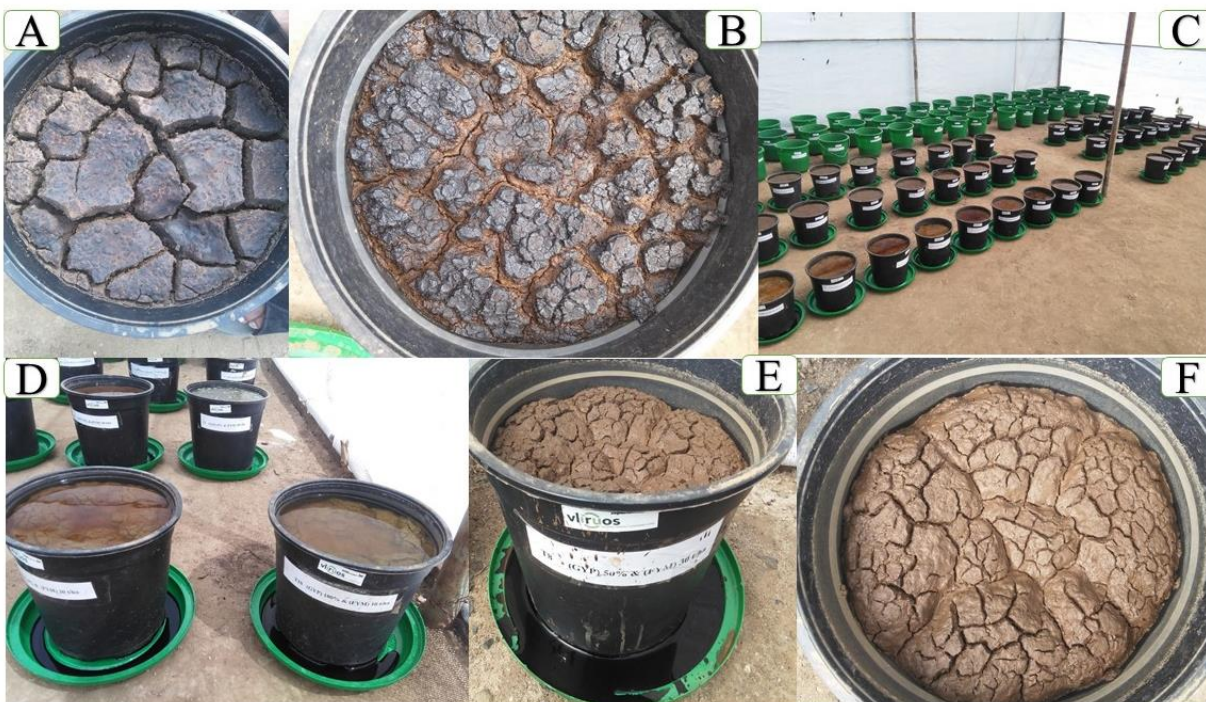


Figure 5. 2: Photos of the incubation and leaching experimental study under shade house conditions

Where: Initial soil for the incubation and leaching study in dark black color (A); incubated soil for three months (90 days) (B); experiment set up by Completely Randomized Design (CRD) (C); leaching incubated sodic soil for one month (28 days) (D); reclaimed sodic soil in light brown color at the top and leachate in dark black color at the bottom of the pot concerning last completed leaching pore volume water (E); reclaimed sodic soil after three months incubation and the one-month leaching study (F).

5.3.4 Multivariate analysis of the effects of combined application of gypsum and farmyard manure on chemical properties of sodic soil after incubation and leaching

5.3.4.1 Correlation between chemical properties of reclaimed sodic soil

The correlations between the chemical parameters of reclaimed sodic soil are shown in Table 5.4 by a Pearson correlation matrix. The exchangeable sodium percentage (ESP) had a strongly positive significant correlation ($p \leq 0.01$) with soil exchangeable Na ($r = 0.95$) while it had a strongly negative significant correlation with exchangeable Ca ($r = -0.68$). Exchangeable Mg showed a significant positive correlation ($p \leq 0.01$) with exchangeable K ($r = 0.63$). On the other hand, exchangeable Ca was negatively correlated with soil pH.

Our study uniformly identified negative linear relationships between the combined application of gypsum (GYP) and farmyard manure (FYM) levels and the levels of exchangeable sodium percentage (ESP), exchangeable sodium (Na^+), pH, and electrical conductivity (EC). Conversely, we observed positive relationships between the levels of GYP and FYM and exchangeable calcium (Ca^{+2}). This indicates the Ex. Ca was negatively related to the pH, EC, ESP, and Ex. Na in the reclaimed sodic soils around Abay and Chamo Lakes Southern Ethiopia Rift Valley. This could be when the combined application of GYP and FYM increases, as well as the pH, EC, and Ex. Na and ESP decrease because of the increased amount of Ex. Ca in the reclaimed sodic soils through displacing the Ex. Na amount.

Previous studies in various locations supported the findings of this study (Bekele et al., 2019; Hailu and Mehari, 2020) which stated that the combined application of gypsum (GYP) and farmyard manure (FYM) levels could have several beneficial effects on soil, including reducing ESP, exchangeable Na^+ , and EC and increasing exchangeable Ca^{+2} .

Table 5. 4: Pearson correlation matrix among soil chemical properties of reclaimed sodic soils

	pH	EC	Ex. Na	Ex. Ca	Ex. Mg	Ex. K	ESP
pH	1.00						
EC	0.46	1.00					
Ex. Na	0.47	0.14	1.00				
Ex. Ca	-0.49	-0.16	-0.68 **	1.00			
Ex. Mg	0.30	-0.01	0.05	0.00	1.00		
Ex. K	0.15	-0.02	0.12	-0.18	0.63 **	1.00	
ESP	0.47	0.15	0.95 **	-0.82 **	-0.13	0.03	1.00

** . Correlation is significant at the 0.01 level.

5.3.4.2 Prediction of exchangeable sodium percentages (ESP)

Prediction of soil exchangeable sodium percentage (ESP) for maintaining quality of soil's chemical properties showed differences among the treatments depending on different levels of amendment contributions, and coefficients of determination in the regression models are indicated in Table 5.5. The study showed that the treatment effect of ESP ($R^2 = 0.95$) alone determines the optimum treatment level required to displace exchangeable sodium from the exchange site. The best estimator models for ESP using treatment level for sodic soil were $\text{ESP} = 1.65 - 0.33\text{gyp}$ for

sole application of gypsum and $ESP = 1.65 - 0.33gyp + 0.28FYM$ for combined application of gypsum with farmyard manure, represented by $gyp100\%$ and $gyp100\% + fym10$ ton/ha treatment levels, respectively (Table 5.5). Moreover, high dimensional variations were observed among the treatments. Consistently, our study identified negative linear relationships between the combined applied gypsum with farmyard manure levels and ESP, exchangeable Na^+ , and EC. In contrast, positive relationships were observed between gypsum (GYP) plus farmyard manure (FYM) levels and exchangeable Ca^{+2} (Figure 5.3).

Combined application of gypsum and farm yard manure could have several beneficial effects on soil, including reducing ESP, exchangeable Na^+ , and EC and increasing exchangeable Ca^{+2} (Bekele et al., 2019; Hailu and Mehari, 2020). These effects are likely because gypsum is a source of calcium, which can help to displace sodium from the soil exchange complex (Gonçalo et al., 2019). Farmyard manure is a source of organic matter, which can improve soil structure and increase the cation exchange capacity (CEC) of the soil (Bashir et al., 2021; Bouajila et al., 2023). A higher CEC means the soil can hold more cations, such as calcium, which helps improve soil nutrient availability and reduce leaching (Jalali and Ranjbar, 2009).

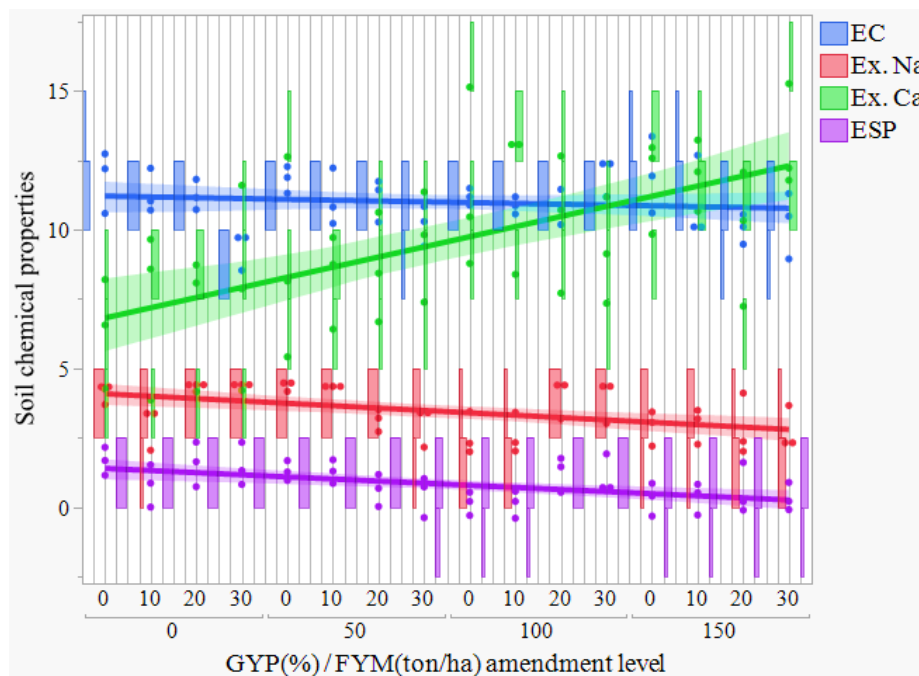


Figure 5. 3: Relationships between the combined application of gypsum (GYP) and farmyard manure (FYM) treatment levels on chemical properties of sodic soil under incubation and leaching study

Where:**❖ Treatment Explanations:**

- Electrical Conductivity (EC): This measures the salt content in the soil. Higher EC indicates higher salinity.
- Exchangeable Sodium (Ex. Na): This represents the sodium ions soil particles hold. High levels can lead to soil dispersion and poor structure.
- Exchangeable Calcium (Ex. Ca): This represents the amount of calcium ions soil particles hold. Calcium is essential for soil structure and plant growth.
- Exchangeable Sodium Percentage (ESP): This is the percentage of sodium ions relative to other cations (like calcium and magnesium) held by soil particles. A high ESP indicates sodic soil conditions.

❖ Gypsum (GYP) Application:

- GYP 0%: No gypsum was applied (0 tons per hectare). This is the control group.
- GYP 50%: Half of the calculated gypsum requirement was applied (5 tons per hectare).
- GYP 100%: The calculated gypsum requirement was applied (10 tons per hectare).
- GYP 150%: 50% more than the calculated gypsum requirement was applied (15 tons per hectare).

❖ Farmyard Manure (FYM) Application:

- FYM 0 tons/hectare: No farmyard manure was applied (control group).
- FYM 10 tons/hectare: Half of the calculated farmyard manure requirement was applied.
- FYM 20 tons/hectare: The calculated farmyard manure requirement was applied.
- FYM 30 tons/hectare: 50% more than the calculated farmyard manure requirement was applied.

Table 5. 5: The regression models used for the prediction of soil amendment level from highly correlated soil chemical properties/variables (ESP, Ex. Na)

Treatment (Gyp% + FYM t/ha)	Model	$I(\alpha)$	$\beta_1 X_1$	$\beta_2 X_2$	R^2	F Value	Pr > F
Gyp100 + FYM10	ESP		1.65–0.33GYP		0.255	15.78	0.000
Gyp100 + FYM10	ESP		1.65–0.33GYP + 0.28FYM		0.257	7.79	0.001
Gyp100 + FYM10	Ex. Na		4.387–0.377GYP		0.234	14.09	0.000
Gyp100 + FYM10	Ex. Na		4.387–0.377GYP + 0.052FYM		0.239	7.0	0.002
Gyp100 + FYM10	Ex. Ca		5.69 + 1.55GYP		0.038	28.33	0.000
Gyp100 + FYM10	Ex. Ca		5.65 + 1.55GYP + 0.020FYM		0.038	13.8	0.000

5.3.4.3 Principal components analysis (PCA) of the chemical properties of reclaimed sodic soil as influenced by different levels of gypsum and farmyard manure

Principal components analysis has been used in a number of studies to assess sodic soils and reclaimed sodic soils (Mahajan et al., 2021; Mohiuddin et al., 2022), and the findings of this study showed that relationships between the investigated variables of the reclaimed sodic soil and combination of each amendment (GYP + FYM). Figure 5.4 shows the results of the principal components (PCs) analysis of the combined application of gypsum and FYM on the chemical properties of reclaimed sodic soil.

The results showed three main principal components (PCs) with eigenvalues greater than 1 which were considered, while the other PCs were neglected. These three PCs explained 86.25% of the studied soil chemical properties' variability: 50.09%, 21.78%, and 14.38% for PC1, PC2, and PC3, respectively. The first principal component (PC1) represented 50.09% of the total variance of the data and showed positive correlations with the following soil variables: ESP, SAR, Ex. Na, and pH. These ESP, SAR, and Ex. Na soil variables were essential contributions, shown in bold in Table 5.6 and light blue in Figure 5.4, to PC1. However, negative correlations and essential contributions were verified for the exchangeable Ca variables, shown in bold in Table 5.6 and light blue in Figure 5.4 to PC1.

Positive correlations and essential contributions were observed for Ex. K and Ex. Mg, with the second component (PC2) explaining 21.78% of the data variation in the exchange site, while PC3 explained 14.38%; positive correlations were observed for pH and EC (Figure 5.4 and Table 5.6).

The PCA biplot also revealed that exchangeable Na, SAR, and ESP were strongly and positively correlated to each other, while the correlations were less strong to EC, pH, Ex. K, and Ex Mg which were strongly and negatively correlated to Ex.Ca (Figure 5.4 and Table 5.6). The variations in the exchangeable complex, soil composition, and soil solution that are confirmed in each treatment are correlated with the changes in the correlation patterns for PC1, PC2, and PC3.

Table 5. 6: Principal component analysis (PCA) of chemical properties of reclaimed sodic soil as influenced by different levels of gypsum and farmyard manure

PCA	Loading Matrix			PCA	Formatted Loading Matrix		
	Prin1	Prin2	Prin3		Prin1	Prin2	Prin3
Eigenvalue	4.01	1.74	1.15	Eigenvalue	4.01	1.74	1.15
Variance (%)	50.09	21.78	14.38	Variance (%)	50.09	21.78	14.38
Cumulative variance (%)	50.09	71.87	86.25	Cumulative variance (%)	50.09	71.87	86.25
pH	0.64	0.34	0.48	ESP	0.97	-0.18	-0.14
EC	0.29	0.10	0.88	SAR	0.97	-0.18	-0.14
Ex. Na	0.93	-0.04	-0.17	Ex. Na	0.93	-0.04	-0.17
Ex. Ca	-0.87	0.00	0.10	pH	0.64	0.34	0.48
Ex. Mg	0.02	0.92	-0.09	Ex. Mg	0.02	0.92	-0.09
Ex. K	0.15	0.83	-0.27	Ex. K	0.15	0.83	-0.27
SAR	0.97	-0.18	-0.14	EC	0.29	0.10	0.88
ESP	0.97	-0.18	-0.14	Ex. Ca	-0.87	0.00	0.10

The values in bold represent essential contributions that are above the expected value if the contributions were uniform.

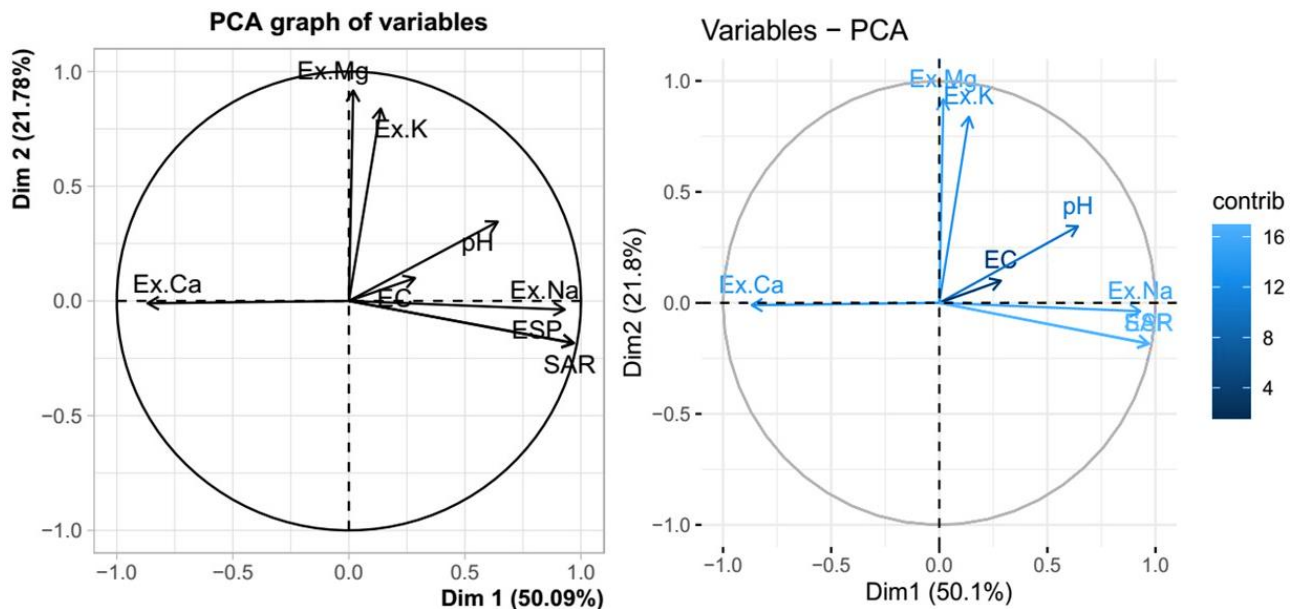


Figure 5. 4: Plot of the chemical characteristics of the reclaimed sodic soil using principal component analysis (PCA) concerning various treatments of farmyard waste and gypsum under leaching and incubation

5.3.4.4 Hierarchical cluster analysis of the chemical properties of reclaimed sodic soil as influenced by different levels of gypsum and farmyard manure treatments

The current study used cluster analysis over a standardized dataset to determine the similarities and differences in the chemical characteristics of the analyzed reclaimed sodic soil. Figure 5.5's dendrogram, produced by agglomerative hierarchical cluster analysis shows the differences between four groups of the investigated reclaimed sodic soil based on soil chemical characteristics due to the combined application of gypsum and FYM (sodic variables—pH, EC, Ex. Na, Ex. Ca, ESP, and SAR). Utilizing multivariate numerical techniques and the R program, soil chemical characteristics were investigated on the reclaimed sodic soil surrounding Abaya and Chamo Lakes.

The datasets on modified sodic soil chemical parameters about various combined amendment were subjected to hierarchical cluster analysis. Four clusters were identified by the hierarchical cluster analysis of the reclaimed sodic soil's distance from soil chemical characteristics. The cluster colored black had gyp100 + fym20, gyp0 + fym0, gyp150 + fym20, and gyp0 + fym10 categorized as one cluster. The green-colored cluster was the second, including gyp50 + fym0, gyp50 + fym10, and gyp100 + fym0. The third cluster in red represents gyp50 + fym30, and gyp100 + fym30, which are categorized as one cluster. The remaining blue-colored clusters were gathered in a single group, indicating the better amendment combination to reclaim sodic soils when comparing the rest of the amendment combinations. The combined application of gyp and fym at 100% gyp and 10 t ha⁻¹ fym is the best amendment to reclaim sodic soils within the same cluster in the dendrogram hierarchical cluster analysis (Figure 5.5). We note that assuming the treatment levels and the reclaimed soils within a cluster have similar properties, they require similar application of the treatment levels and the same management. This hierarchical cluster analysis provides a valuable framework for understanding the complex interactions between soil amendments and sodic soil properties. Using this information, land managers can make more informed decisions about sodic soil reclamation and improve the sustainability of agricultural practices.

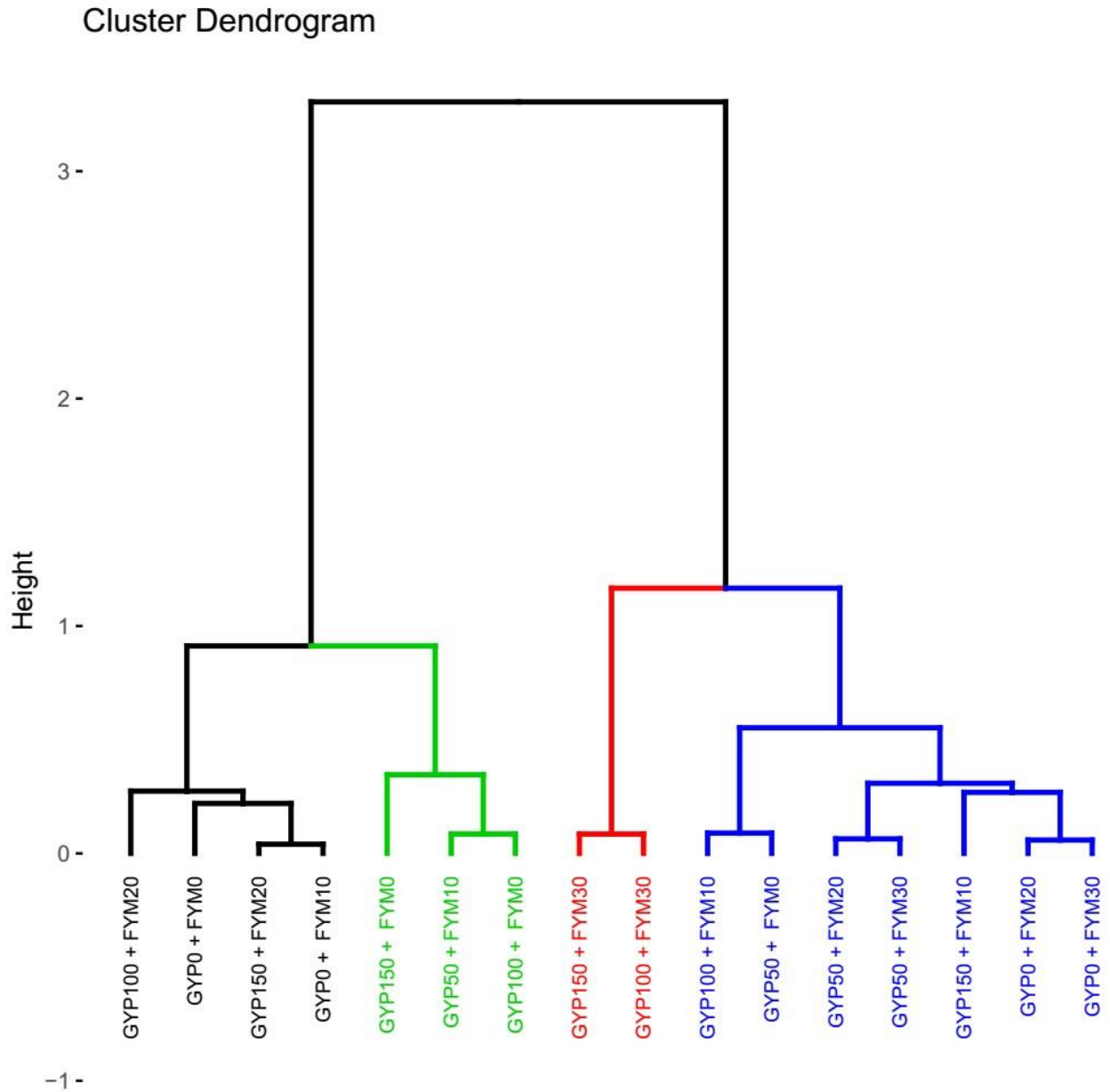


Figure 5. 5: Cluster dendrogram (Ward's method) of chemical properties of reclaimed sodic soil with different levels of gypsum and farmyard manure under incubation and leaching experiment

Where: different color lines have noted that assuming the treatment levels and the reclaimed soils within a cluster have similar properties, they require similar application of the treatment levels and the same management.

5.3.4.5 K-Means clustering of the chemical properties of reclaimed sodic soil as influenced by different levels of gypsum and farmyard manure treatments

We utilized K-means clustering to analyze reclaimed sodic soil along with various amendments, aiming to identify the optimal amendment level for the reclamation of sodic soils in the study area. K-means clustering is a widely used algorithm that partitions data points into a predetermined number of clusters, denoted as “K.” Hence, the K-means cluster analysis based on the combined amendments separated by the variance of treatments on the first (PC1) and second principal components explained 50.09% and 21.78%, respectively (Figure 5.6). The combined treatments from cluster 1 in red, including gyp 150% + fym 30 t ha⁻¹ and gyp 100% + fym 30 t ha⁻¹, and cluster 2 in green, including gyp 0% + fym 20 t ha⁻¹, gyp 50% + fym 30 t ha⁻¹, gyp 0% + fym 30 t ha⁻¹, gyp 0% + fym 20 t ha⁻¹, gyp 100% fym 10 t ha⁻¹, and gyp 150% + fym 10 t ha⁻¹ treatment combination were located on the left bottom and top side of the PCA plane, respectively. Better treatment combinations to reclaim sodic soils were grouped in cluster 2 in green, from which treatment combination at gyp 100% + fym 10 t ha⁻¹ was the best treatment amendment combination. cluster 3, in blue, including gyp 150% + fym 20 t ha⁻¹, gyp 50% + fym 0 t ha⁻¹, gyp 100% + fym 20 t ha⁻¹, gyp 0 % + fym 10 t ha⁻¹, and gyp 0 % + fym 10 t ha⁻¹ treatment combination and cluster 4 including gyp 50 % + fym 10 t ha⁻¹, gyp 100% + fym 0 t ha⁻¹ and gyp 150 + fym 0 t ha⁻¹ treatment combination, in purple, treatments were in the right bottom and top of the PCA plane and did not differ much (Figure 5.6).

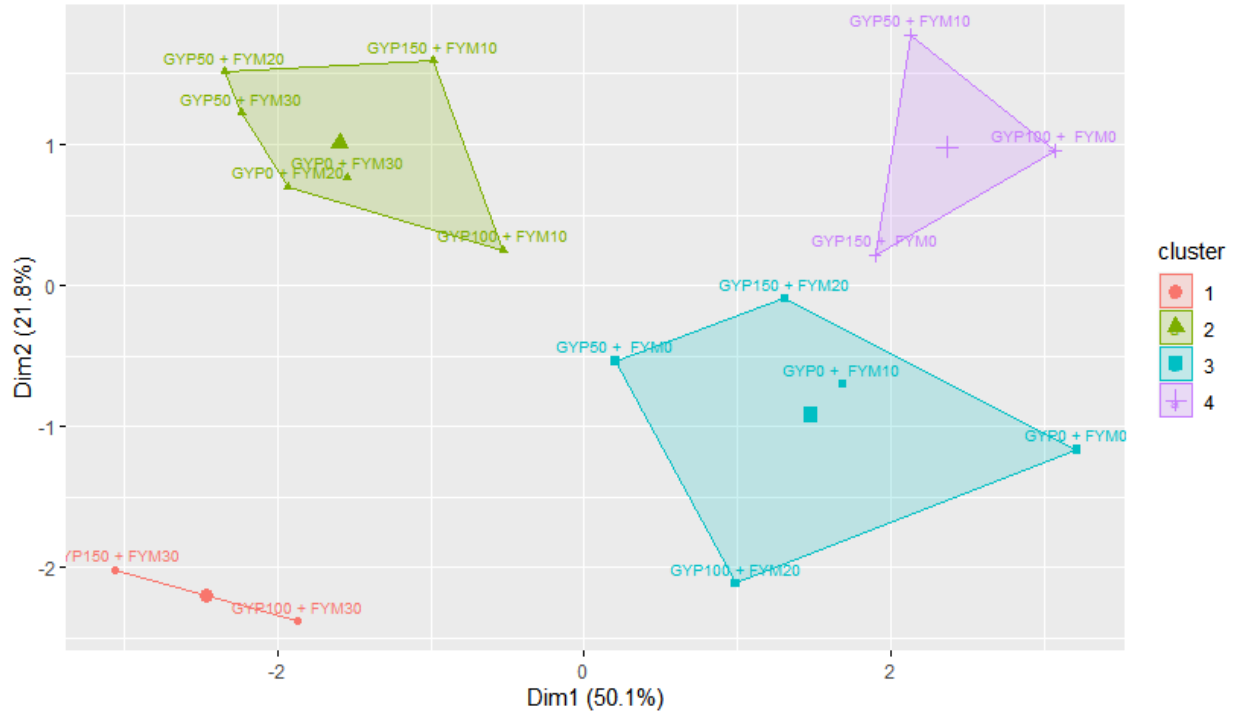


Figure 5. 6: K-means cluster of reclaimed sodic soil chemical properties concerning different gypsum (GYP) and farmyard manure (FYM) treatments under incubation and leaching study

5.4 Conclusions

In dry and semi-arid regions, sodic soils are problematic in reducing production, and harming the natural and agricultural ecosystems. Adding farm yard manure and agricultural grade gypsum to sodic soils can raise the calcium content of the soil and replace the sodium content. The present study investigated the effects of gypsum and farm yard manure on pH, electric conductivity, and exchangeable sodium percentage in sodic soil. The findings indicate that combined application of gypsum and farmyard manure considerably impacted the chemical characteristics of sodic soils. Applying 10 ton FYM ha⁻¹ (organic source) along with 100% (10 ton GYP ha⁻¹) of gypsum (a chemical amendment) simultaneously can lead to better outcomes. The electrical conductivity of the soil and the percentage of exchangeable sodium declined after three months of incubation and leaching.

A combined application rate can reduce the sodium content and increase the amount of plant nutrients (Ca, Mg, and K) in the soil. The best estimator models to reduce ESP for the sodic soil using amendment level were $ESP = 1.65 - 0.33 \text{ GYP}$ for sole application of gypsum and $ESP =$

1.65–0.33 GYP + 0.28 FYM for combined application of gypsum with farmyard manure. Agglomerative hierarchical and K-means cluster analysis indicate that they require similar application of the treatment levels and the same management, assuming the treatment levels and the reclaimed soils within a cluster have similar properties. Based on research findings, farmyard manure (10 ton FYM ha⁻¹) and an appropriate amount of gypsum (100% (10 ton GYP ha⁻¹)) can assist managing sodic soils while supporting sustainable crop production. However, further study on changes in microorganisms after treatments and cost analysis should be considered in future research work to draw sound conclusions.

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6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The key biophysical requirement for increase food production in Sub-Saharan African countries is the restoration of soil fertility. In Ethiopia, agriculture is fundamental to the national economy, and farming has depended on natural resources for centuries. The sustainability of any farming system ultimately depends on soil, which is a dynamic resource that takes time to replenish. Soil plays a significant role in vegetation productivity, land use, water movement, and water quality. Soils significantly threaten the world's agricultural productivity due to salinity and sodicity, particularly in Sub-Saharan countries' arid and semi-arid regions. This can reduce crop yields, leading to biodiversity loss and environmental degradation around Abaya and Chamo Lakes, Southern Ethiopian Rift Valley region. One way to tackle this problem is by assessing the extent and severity of salinity and sodicity of soils, which can help prioritize areas for reclamation and develop targeted management strategies. Therefore, assessing and characterizing agricultural soils is vital to ensure long-term agricultural sustainability and food security, especially in a study area with increasing challenges of land degradation. Soil salinity and sodicity are also a common issues faced by farmers, as these soils often lack essential nutrients and have poor physical properties that hinder crop growth and yield. Farmers can use appropriate fertilizers tailored to the nutrient requirements of these soils to enhance crop productivity, but studies need to quantify the nutrient contents in the soils of study area. Hence, this study was initiated to assess the nutrient status in soils by analyzing soil samples.

Mapping and geographical analysis of soils are crucial instruments that offer insightful information for practical management approaches. Tools aid land managers in making informed decisions on crop selection, irrigation techniques, and management strategies, identifying salinization risk areas, guiding remediation and reclamation efforts, and promoting sustainable agricultural land use. Additionally, spatial analysis can track changes in the extent and intensity of salt-affected soils over time, evaluating the effectiveness of management interventions. This approach also benefits stakeholders such as farmers, researchers, and policymakers by enabling informed decision-making, funding remediation, and reclamation efforts, and promoting the development of new technologies and management practices in the study area. In connection with this, sodic soils are a considerable challenge for agriculture worldwide due to their high sodium content.

To ensure food security and sustainable land management, it is essential to focus on reclaiming these soils. To do this, amendment resources such as gypsum and farm yard manure should be used. These resources can help reduce the sodium content, improve soil structure, and enhance nutrient availability. However, it's important to note that the effectiveness of these resources can vary depending on soil type, climate, and application methods. Understanding these factors can optimize soil reclamation strategies and improve crop yields, and sustainable soil management practices.

The present study was initiated to characterize, map, and reclaim soils in the study area. Four independent studies were conducted based on the criteria set for agricultural soil studies. Objective-based soil samples were collected from three depths: 0-20, 20-40, and 40-60 cm from 5 representative pits and 0-20 and 20-40 cm through a systematic sampling technique for the first and second objectives, respectively. Additionally, soil samples were collected from 0-20 cm by grid sampling techniques. Furthermore, soil samples were also collected from pots incubated for three months and leached for one month for the fourth objective. The laboratory soil analysis was done using standard laboratory procedures. The soil analysis results were assessed, analyzed, and interpreted in accordance with a set of defined analytical standard procedures for soil data. Using the statistical analysis software R, PCA and clustering were applied to the soil study results. Calculating correlation coefficients allowed the determination of relationships between the chemical properties of the soils. The laboratory results were imported into a GIS environment, along with the type and intensity of salt problems in the studied soils, and the spatial distribution of soil fertility status were determined by entering the data into Microsoft Excel with the corresponding coordinates (Latitude and Longitude).

Spatial prediction and mapping of the un-sampled surface soils were done from laboratory point data in a GIS context using interpolation techniques. The ordinary kriging algorithm in QGIS software was used to predict and map the un-sampled surface from laboratory point data. Two-way ANOVA was used to elucidate the appropriate and best amendment level for reclamation of the sodic soil in incubation and leaching study. The significance was tested using differences between treatments with subsequent mean separation by LSD test at 0.05.

The first study was "Characterization of Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley." Soil pits were utilized to evaluate salinity and sodicity distribution in agricultural

soils in the study area, which revealed the need for drainage of the soils. The study also revealed brownish to black soil color in agricultural soils, blocky structure due to higher clay content, and soil texture with silt-to-clay ratios greater than 0.3 indicating the soils are young. Most of the soils of the study sites were highly alkaline, high in sodium and available phosphorous contents, with low organic carbon, very low total nitrogen content, and low exchangeable calcium. Sodium was the dominant soluble cation, with Na^+ content decreasing with depth due to leaching, while Cl^- was the dominant anion. Given that the soils in a cluster possess similar properties, they should be managed similarly. The study elucidated salt-affected soils of the area requires salt removal through drainage and leaching, as salt content restricts crop growth. Thus, choosing salt-tolerant crops and timber plants, and adding organic matter to improve soil productivity and production could be recommended in salt-affected parts of the area.

The second study was "Nutrient Contents and Mapping of Fertility Status of Soils around Abaya and Chamo Lakes, Southern Ethiopia Rift Valley." Analyses of soil properties and their distribution focusing on nutrient content and fertility status revealed clay, heavy clay, and sandy clay loam textures. The surface soils had higher available water holding capacity. The soils had high alkalinity and EC values, and low exchangeable calcium in some study areas; hence, extra calcium may be needed for healthy plant growth.

On the other hand, high sodium content might have a detrimental effect on crop yield. There were also significant amounts of iron, manganese, and copper as well as high soil CEC and potassium availability. The results of the current study allow for an evaluation of how the availability of soil nutrients has changed over time. This analysis may reveal areas where there has been a gradual decline in soil fertility. To monitor changes in soil fertility status, routine soil testing and mapping should be implemented. Additionally, the EthioSIS data should be updated and refined with new information to ensure its accuracy and usefulness. By following these recommendations, Ethiopia can manage soil fertility more effectively, improve agricultural yields, and promote food security. While sodicity and salinity necessitate reclamation, the results also suggest adding organic matter to enhance soil structure, water retention, and nutrient availability. Deficient levels of nitrogen in the study area suggest that plants need more nitrogen fertilizer from the soil. Therefore, crops may still require additional nitrogen fertilizer for maximum production. The third study "Spatial Analysis and Mapping of Intensity and Types of Agricultural salt-affected Soils around Abaya and

Chamo Lakes, Southern Ethiopia Rift Valley" was aimed at identifying and mapping salt-affected soils around Abaya and Chamo Lakes, to manage soil salinity/sodicity and support site-specific interventions. This study was initiated based on the findings of the first and second studies to identify and map the intensity and type of salts around the Abaya and Chamo Lakes Southern Ethiopia Rift Valley. The soils of the area is dominated by alkaline soil reactions, with low to high-risk soil sodicity and high exchangeable sodium values, all affecting crop growth and productivity. Based on the findings of the third study, 62% of soils around Abaya and Chamo Lakes South Ethiopia Rift Valley were salt-free, which indicates the hope for potential crop production in the area. However, the spatial heterogeneity of the salt-affected soil classes in the area necessitates site-specific reclamation measures to address salinity and sodicity issues and ensure soil productivity. Use of organic matter, chemical amendments, and phytoremediation can also improve soil structure and drainage, and thereby reduce salt accumulation. Leaching with high-quality irrigation water could also be recommended.

The fourth study was titled "Elucidating of Amendment Resources for Reclaiming Efficacy of Sodic Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley." The study showed that combined application of gypsum and farm yard manure significantly impacted soil chemical properties, decreasing electrical conductivity, exchangeable sodium, and ESP values. Applying 10 t FYM ha⁻¹ organic source and gypsum at 100% GR rate improved soil nutrient content and reduced sodium content. The most effective estimator models for reducing ESP in sodic soil using amendment levels were $ESP = 1.65 - 0.33 \text{ GYP}$ for gypsum application and $ESP = 1.65 - 0.33 \text{ GYP} + 0.28 \text{ FYM}$ for gypsum combined with farm yard manure. Thus, managing sodic soils by incorporating appropriate farm yard manure levels (10 t ha⁻¹) and gypsum (10 t ha⁻¹ or at 100% GR) could enhance sustainable crop production. However, 10 t FYM ha⁻¹ was also recommended to the farmers since it is affordable and feasible to the economic capacity of the individual farmers.

Based on the results of the study, the following recommendations were forwarded.

- ❖ Soils around Abaya and Chamo Lakes, Southern Ethiopia Rift Valley are different in morphology, physical and chemical properties, and therefore, a site-specific soil characterization should be conducted to adopt different crop production technologies.

- ❖ The fertility status of the soils of the study area revealed hope for crop production through appropriate soil management of soils, but detailed nutrient management technologies are needed.
- ❖ Regular soil testing and mapping should be conducted to track changes in soil fertility.
- ❖ The EthioSIS data should be updated and improved with new information to ensure its accuracy and relevance.
- ❖ The extent, nature, and distribution of salt-affected soil in the study area differ in intensity and type of salt; hence, further detailed technology-supported study is required for soil salinity and sodicity management to fill the gap left by this study.
- ❖ The sodic soil reclamation experiment revealed significant effects of applying gypsum and farmyard manure. However, for the efficiency of the amendment materials, and their potentials should be verified under field conditions.

7. APPENDICES

Appendix Table 1. 1 : Climate data around Abaya and Chamo lakes, South Ethiopia Rift Valley (1983–2020 average) (Source: AMU-IUC Project meteorology station)

Months	Abaya Lake Area			Chamo Lake Area		
	RF (mm)	Tmax (°C)	Tmin (°C)	RF (mm)	Tmax (°C)	Tmin (°C)
January	12.5	31.4	14.9	9.0	33.3	17.0
February	21.5	32.3	15.7	20.0	34.6	17.9
March	63.5	32.2	16.2	65.5	35.1	18.8
April	146.5	30.8	16.6	152.0	33.9	18.9
May	118.5	29.5	16.5	133.5	33.1	18.7
June	77.0	28.0	16.2	83.0	32.9	18.5
July	85.0	27.1	16.0	99.5	31.5	18.1
August	80.0	27.9	15.9	107.0	30.8	17.8
September	92.0	29.1	15.7	93.5	31.5	17.5
October	106.5	29.7	15.3	127.5	32.4	17.4
November	36.0	30.4	14.5	62.5	32.7	17.0
December	23.5	30.7	14.3	29.0	33.1	16.7

RF is rainfall; Tmax is maximum temperature; and Tmin is minimum temperature

Appendix Table 2. 1: Descriptive statistic of selected chemical characteristics of agricultural soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley

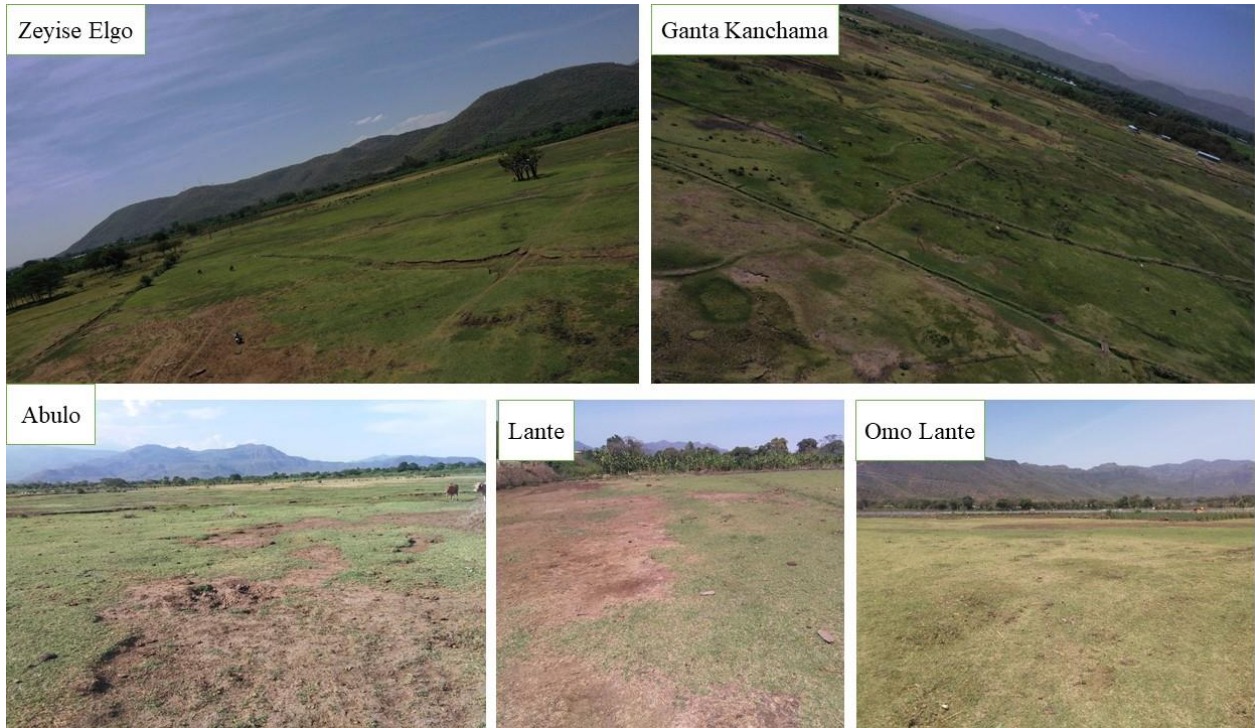
Depth	0-20 cm				20-40 cm				40-60 cm			
	Des. S	N	Min	Max	Mean \pm SD	N	Min	Max	Mean \pm SD	N	Min	Max
pH	5	7.70	10.30	9.52 \pm 1.11a	5	8.60	9.90	9.56 \pm 0.54a	5	8.30	9.60	9.26 \pm 0.54a
EC	5	1.02	8.21	3.92 \pm 2.86a	5	0.92	2.34	1.48 \pm 0.54b	5	0.67	1.86	1.36 \pm 0.45b
Ex.Na	5	4.16	93.68	43.44 \pm 33.94a	5	17.18	61.42	40.98 \pm 18.67a	5	6.68	53.92	39.33 \pm 19.89a
Ex.K	5	0.76	2.32	1.41 \pm 0.57a	5	0.68	1.27	1.03 \pm 0.27a	5	0.50	1.22	0.96 \pm 0.29a
Ex.Ca	5	2.86	25.28	9.16 \pm 9.23a	5	2.13	10.52	4.75 \pm 3.61a	5	0.59	7.74	3.58 \pm 3.31a
Ex.Mg	5	1.32	10.79	4.27 \pm 3.94b	5	2.62	13.29	5.47 \pm 4.43ab	5	3.41	13.90	6.10 \pm 4.42a
CEC	5	44.80	64.90	50.84 \pm 8.01a	5	44.30	52.20	47.10 \pm 2.99a	5	40.90	55.90	46.12 \pm 6.46a
BS	5	74.00	153.00	112.20 \pm 37.64a	5	85.00	131.00	110.20 \pm 21.66a	5	71.00	145.00	109.00 \pm 31.09a
Av.P	5	5.64	77.29	39.82 \pm 26.01a	5	2.38	78.98	30.13 \pm 29.42a	5	8.28	23.39	16.20 \pm 7.24a
OC	5	0.68	1.88	1.12 \pm 0.52a	5	0.28	0.91	0.53 \pm 0.23b	5	0.21	0.97	0.52 \pm 0.29b
CaCO ₃	5	1.10	3.80	2.56 \pm 0.98a	5	2.00	2.70	2.30 \pm 0.26a	5	0.10	2.40	1.52 \pm 0.96a
SAR	5	1.07	64.80	24.71 \pm 24.66a	5	5.52	36.94	22.60 \pm 14.49a	5	2.03	38.13	22.73 \pm 14.49a
ESP	5	0.32	95.26	35.54 \pm 36.74a	5	6.95	53.75	32.40 \pm 21.58a	5	1.75	55.53	32.60 \pm 21.59a

Means within a row followed by the same letters are not significantly different at $P \leq 0.05$.

Appendix Table 2. 2: Physico-chemical properties of soils around the pits

pH (H ₂ O)	EC dS/m	Sand	Silt	Clay	Soil texture	OC	TN	ESP	Ca	Mg	K	Na	CEC	Av. P (mg kg ⁻¹)
		%				%			cmolc kg ⁻¹					
Pit, CL01														
10.30	3.18	62	6	32	SCL	0.54	0.03	138.10	3.99	1.65	1.25	63.90	46.00	20.30
Pit, CL02														
10.60	4.00	6	30	64	HC	1.01	0.06	116.69	3.19	2.18	1.16	60.80	52.10	83.87
Pit, AL01														
8.80	5.30	26	22	52	Clay	1.32	0.04	81.42	9.95	5.78	1.33	40.71	50.00	9.12
Pit, AL02														
8.10	1.55	28	28	44	Clay	1.22	0.04	19.10	21.6	8.33	1.18	9.82	49.30	4.23
Pit, AL03														
9.4	6.01	42	6	52	Clay	1.03	0.04	114.01	9.25	4.32	2.26	58.52	51.30	75.44

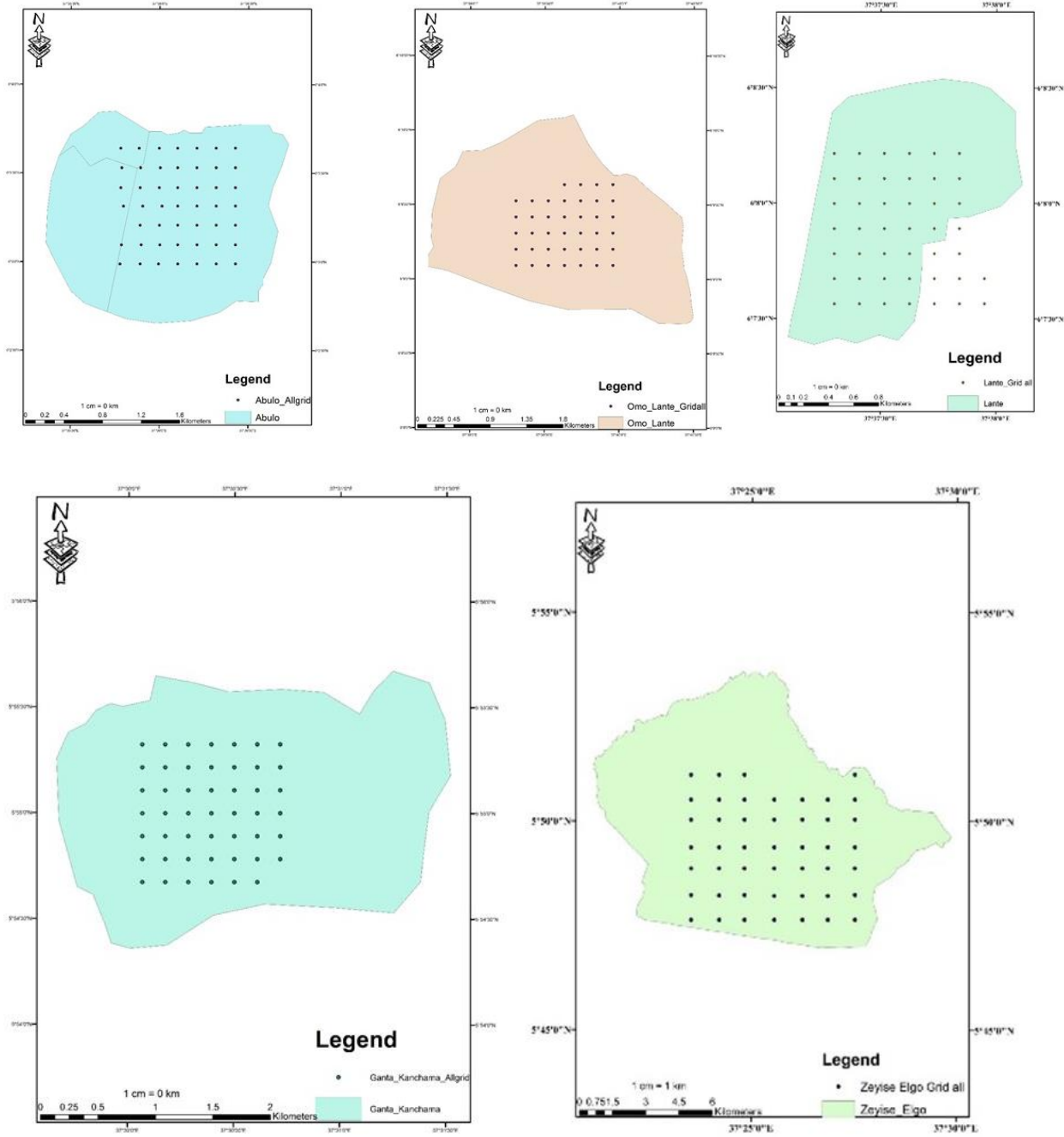
Where, SCL = Sandy clay loam, HC = Heavy clay



Appendix Figure 2. 1: Partial photos of the study area concerning sampling sites (photos by drone)



Appendix Figure 2. 2: Typical agricultural salt-affected soil indicating photos



Appendix Figure 4. 1: A grid soil sampling scheme with respect to sampling sites within the study area



Appendix Figure 5. 1: Study area supervision by advisors in the field, laboratory, and experiments in the shade house



Appendix Figure 5. 2: The potential of the study area for crop production (photos by drone)

Research Article

Assessment and Characterization of Agricultural Salt-Affected Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley

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Soil salinity/sodicity is becoming a challenge for crop production in Ethiopia's semi-arid and arid regions. However, more information on soil salinity/sodicity needs to be available around Abaya and Chamo Lakes, South Ethiopia Rift Valley. This study aimed to assess and characterize soil salinity/sodicity and determine salt-affected soils' morphological, physical, and chemical properties. The representative soil pits that were 60 * 60 * 60 cm in size were examined, and samples were taken from 0–20, 20–40, and 40–60 cm depths based on the criteria set for agricultural salt-affected soil studies. The soil properties determined include soil color, structure, consistency, bulk density, particle density, porosity, texture, pH, EC, SAR, ESP, CEC, BS, OC, TN, available P, CaCO₃⁻, exchangeable bases, and soluble ions (Na⁺, Ca²⁺, Mg²⁺, K⁺, Cl⁻, SO₄⁻², NO₃⁻, CO₃⁻², and HCO₃⁻). The soil-analyzed results were rated and interpreted following a guide to standardized analysis methods for soil data. The results of this study reveal that the soils had considerable heterogeneity in soil morphological, physical, and chemical properties. The soils of the study site were highly alkaline and had very high sodium content, very high CEC value, and low levels of organic carbon and exchangeable calcium. The dominant soluble cation was sodium, followed by magnesium, calcium, and potassium in all soil depths of the pits. Similarly, Cl⁻ was dominant among the anions throughout the soil depth, followed by HCO₃⁻, SO₄²⁻, and NO₃⁻. The findings of this study imply that removing sodium and salts from the soil depth may improve the salt-affected soils' productivity in the study area. Application of organic amendments, including manures and crop residues, may also be beneficial in increasing fertility and organic matter content.

1. Introduction

Soil degradation is a major global problem in nearly all developing countries where large proportions of the population get their livelihoods directly from the soil [1]. After soil erosion, soil salinity is the second-largest factor in land degradation, and it has been linked to the downfall of agricultural communities for 10,000 years [2]. Salt-affected soils are distributed worldwide, and no continent is free from this problem under almost all climatic conditions [3, 4]. However, their distribution is relatively more extensive in the arid and semi-arid regions than in the humid regions. Especially in arid and semi-arid regions,

salt-affected soils often occur on irrigated lands, where annual rainfall is insufficient to meet plants' evaporation needs and salts' leaching [4].

The sources of salts append saline parent materials, extreme weathering of rocks and primary minerals, fossil salts of retired marine and lacustrine deposits, atmospheric deposition, a troupe of saline sediments in catchment areas, irrigation waters, and fertilization [5]. Irrigation water or fertilization may also introduce salts into the arable lands [4]. A large land area is becoming unproductive yearly because of salinity and sodicity. Soil salinization is a growing issue whenever irrigation is used as a result of the reliance on rain-fed agriculture, especially in arid and semi-arid regions. Soil degradation due to salinity and

Article

Elucidating Amendment Resources for Reclaiming Efficacy of Sodic Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley

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Abstract: Background: Sodic soils are harmful to agricultural and natural environments in Ethiopia's semi-arid and arid regions, leading to soil degradation and reduced productivity. This study investigated how amendment resources could help improve the chemical properties of sodic soils around the Abaya and Chamo Lakes in the South Ethiopia Rift Valley. Methods: A factorial experiment was conducted to study the effects of gypsum (GYP) and farmyard manure (FYM) on sodic soil reclamation. The experiment had four levels of GYP (0, 50, 100, and 150%) and four levels of FYM (0, 10, 20, and 30 tons ha⁻¹), with three replications. The pots were incubated for three months and leached for one month, after which soil samples were collected and analyzed for chemical properties. ANOVA was performed to determine the optimal amendment level for sodic soil reclamation. Results: The study found that applying 10 ton FYM ha⁻¹ and gypsum at 100% gypsum required (GR) rate resulted in a 99.8% decrease in exchangeable sodium percentages (ESP) compared to untreated composite sodic soil and a 1.31% reduction over the control (GYP 0% + FYM 0 ton ha⁻¹). As a result, this leads to a decrease in soil electrical conductivity, exchangeable sodium (Ex. Na), and ESP values. The results were confirmed by the LSD test at 0.05. It is fascinating to see how different treatments can have such a significant impact on soil properties. The prediction models indicate that ESP's sodic soil treatment effect ($R^2 = 0.95$) determines the optimal amendment level for displacing Ex. Na from the exchange site. The best estimator models for ESP using sodic soil treatment levels were $ESP = 1.65 - 0.33 \text{ GYP}$ for sole gypsum application and $ESP = 1.65 - 0.33 \text{ GYP} + 0.28 \text{ FYM}$ for combined GYP and FYM application, respectively. Conclusion: The study found that combined GYP and FYM applications reduced ESP to less than 10% in agriculture, but further research is needed to determine their effectiveness at the field level.

Keywords: sodic soil; soil properties; arid regions; gypsum; farmyard manure



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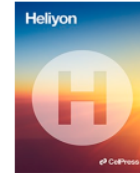
1. Introduction

A balanced nutrient application is necessary for long-term agricultural production and soil health since plant nutrients are essential to crop productivity [1]. Nutrient availability in the soil is influenced by the physico-chemical characteristics of the soil and management factors [2]. Since salt ions are more prevalent in alkaline soil, crop growth is limited by the availability of nutrients [3]. The higher concentrations of salt cations such as sodium (Na), calcium (Ca), and magnesium (Mg), along with the associated chloride (Cl), sulfates (SO₄), carbonate (CO₃), and bicarbonate (HCO₃) anions, restrict the availability of critical plant nutrients [4]. Sodic soils are a severe problem, particularly in dry and semi-arid areas [5]. Exchangeable sodium percentages (ESP) > 15, an electric conductivity (EC) of 4 dS m⁻¹, and a saturation extract sodium adsorption ratio (SAR) lower limit of 13 are all characteristics of sodic soils. Therefore, the fundamental problem in these soils is Na⁺ [6].



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Research article

Spatial analysis and mapping of intensity and types of agricultural salt-affected soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley

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ABSTRACT

Purpose: Salt-affected soils have significant enough salt concentrations to impact other land and soil resource uses, plant health, soil characteristics, and water quality. Consequently, a study was carried out in the South Ethiopian Rift Valley area around the lakes of Abaya and Chamo to determine the intensity and the types of salt-affected soil and map their spatial distributions.

Methods: At 0–20 cm depths, a grid soil sampling scheme was employed to gather data from agricultural soils affected by salt. An adequately spaced grid cell of 200 m*200 m or seven transects, with seven samples collected every 200 m on each sampling site, was generated by the QGIS software's Fishnet tool, and an auger collected 226 soil samples from the proposed 245 soil sampling points. The analysis and interpretation of the data were done using both statistical and geostatistical methods. The un-sampled surface was predicted and mapped from laboratory point data using the standard Kriging algorithm in QGIS.

Results: According to the results, the soil in the study area was rated as strongly alkaline and moderately alkaline in the reaction. The coefficient of variation (CV) was the lowest for soil pH. Except for the Ganta Kanchama site, low CV (<10 %) confirmed the similarity of pH values throughout all research areas. The EC values depicted that the study area is slightly saline except for the Ganta Kanchame site, which rated moderately saline to strongly saline. The variability of soil EC rated moderate to strong variation for the studied area. The exchangeable sodium percentage (ESP) values distribution between the study sites demonstrates considerable variability and difference. The area is dominated by low to high-risk rate soil sodicity, as evidenced by the soil ESP CV of the studied area, which was >100 % and showed significant variability among the samples. Out of 2274.65ha of the studied area, the type of salt 62.28 %, 26.09 %, 10.99 %, and 0.63 % were categorized as non-saline non-sodic, saline-sodic, sodic, and saline, respectively. Following saline-sodic, sodic, and saline soils, respectively, non-saline and non-sodic soils comprise most of the investigated areas.

Conclusions: The result indicates almost all the salt-affected areas were situated in relatively lower slope areas exhibiting a flat to almost flat slope (0–2%). The study's findings are that the studied area needs specific soil management strategies to boost the salinity and sodicity problems around the study area and recommended reclamation techniques as the extent of the problems.

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Appendix Figure 6. 3: Published article three



SOIL MICRONUTRIENT CONTENT ANALYSIS AND MAPPING OF AGRICULTURAL SALT-AFFECTED SOILS AROUND ABAYA AND CHAMO LAKES, SOUTH ETHIOPIA RIFT VALLEY †

[ANÁLISIS DEL CONTENIDO DE MICRONUTRIENTES DEL SUELO Y MAPEO DE SUELOS AGRÍCOLAS AFECTADOS POR LA SAL ALREDEDOR DE LOS LAGOS ABAYA Y CHAMO, EN EL VALLE DEL RIFT DEL SUR DE ETIOPÍA]

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SUMMARY

Background. Salt-affected soils cause a significant portion of land to become unproductive yearly; its impact is severe in sub-Saharan African nations, especially the arid and semiarid lowlands, and the Rift Valley regions of Ethiopia are typically host to naturally salt-affected areas. **Objective.** To analyze the micronutrient content and map the micronutrient fertility status of agricultural salt-affected soils around Abaya and Chamo Lakes South Ethiopia Rift Valley. **Methodology.** A systematic sampling technique was employed to obtain 300 soil samples for the investigation from two depths (0-20 and 20-40cm), with a 600m sampling interval, of which 30 were used. The research data was analyzed using the application of standardized analytical procedures for soil data and descriptive and geostatistical techniques. **Results.** According to the study, there is low zinc available in the soil but an ample amount of iron, manganese, and copper. In addition, the study's findings revealed that, whereas the remaining micronutrient regional variability is found at long distances, available iron exhibited a regional variation in soil quality at small distances. **Implications.** The study suggests applying organic matter for better soil structure, water retention, and nutrient availability. Moreover, the results recommend that soils affected by salt might recover using various materials. **Conclusions.** In the study areas, zinc fertilizer may still be needed for an optimal yield even though the research area has low amounts of zinc fertilizer. The study concluded with management recommendations to minimize the adverse effects of very high micronutrient content on human health and plant growth.

Key words: Kriging, nutrient variability; salt-affected soils; soil micronutrient; special dependency.

RESUMEN

Antecedentes. Los suelos afectados por la sal hacen que una porción importante de la tierra se vuelva improductiva cada año; su impacto es severo en las naciones del África subsahariana, especialmente en las tierras bajas áridas y semiáridas, y las regiones del Valle del Rift en Etiopía suelen albergar áreas naturalmente afectadas por la sal. **Objetivo.** Analizar el contenido de micronutrientes y mapear el estado de fertilidad de los micronutrientes de los suelos agrícolas afectados por la sal alrededor de los lagos Abaya y Chamo, el valle del Rift del sur de Etiopía. **Metodología.** Se empleó una técnica de muestreo sistemático para obtener 300 muestras de suelo para la investigación a dos profundidades (0-20 y 20-40 cm), con un intervalo de muestreo de 600 m, de las cuales se utilizaron 30. Los datos de la investigación se analizaron mediante la aplicación de procedimientos analíticos estandarizados para datos de suelos y técnicas descriptivas y geoestadísticas. **Resultados.** Según el estudio, hay poco zinc disponible en el suelo, pero una gran cantidad de hierro, manganeso y cobre. Además, los hallazgos del estudio revelaron que, mientras que la variabilidad regional de los micronutrientes restantes se encuentra a largas distancias, el hierro disponible exhibió una variación regional en la calidad del suelo a distancias pequeñas. **Implicaciones.** El estudio sugiere aplicar materia orgánica para una mejor estructura del suelo, retención de agua y disponibilidad de nutrientes. Además, los resultados sugieren que los suelos afectados por la sal podrían recuperarse utilizando diversos materiales. **Conclusiones.** En las áreas de estudio, es posible que aún se necesite fertilizante de zinc para obtener un rendimiento óptimo, aunque el área de investigación tenga cantidades bajas de fertilizante de zinc. El estudio concluyó con recomendaciones de gestión

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